AN ABSTRACT OF THE THESIS OF

JOHN STEED, JR. FOR THE DEGREE OF MASTER OF SCIENCE in Bioresource Engineering presented on August 9, 1992.

Title: Methane Emissions From Typical Manure Management Systems

Abstract approved: Redacted for privacy

Andrew G. Hashimoto

Methane is the most abundant organic chemical in the earth's atmosphere. Its abundance in the atmosphere is increasing with time and has reached levels not seen in recent geological history. The methane is produced both naturally, and anthropogenically. One of the sources of anthropogenic methane is manure from domesticated animals. Casada and Safley (1990) estimated the amount of methane generated from this source. This was done by estimating the Methane Conversion Factor (MCF) typically achieved by various waste management systems. This study was done to evaluate those estimates of the MCF. The MCF's for the most dominant of disposal methods, rangeland/pasture disposal, were much lower than the earlier estimates. Other waste management systems, such as solid storage and liquid slurry storage had much higher MCF's, at 20° and 30° C. However, these waste management methods are more prevalent in parts of the world where the average annual temperature is closer to 10° C. At that temperature, the MCF is

negligible in all waste management systems. This study showed that the previously reported estimates of MCF for some waste management systems were higher than what was actually the case. Consequently earlier estimates of the amount of methane generated from manures were higher than what this study found.

Methane Emissions From Typical Manure Management Systems

by

John Steed, Jr.

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed August 9, 1993
Commencement June, 1994

Approved:

Redacted for privacy

Professor of Bioresource Engineering in charge of major

Redacted for privacy

Head of department of Bioresource Engineering

Redacted for privacy

Dean of Graduate School

Date thesis is presented August 9, 1993

Typed for John Steed Jr., by John Steed, Jr.

TABLE OF CONTENTS

LIST OF FIGURES

Figure		Page

LIST OF TABLES

Methane Emissions From Typical Manure Management Systems

Introduction

Greenhouse gasses are those which trap energy radiated from the sun. These gasses tend to be transparent to the shorter wavelengths, but tend to absorb the longer, infrared radiation. Water vapor and carbon dioxide (CO_2) tend to be the most important natural greenhouse gasses because of their abundance. Since the industrial revolution, which began around 1860, the concentration of CO_2 and other greenhouse gasses have increased in the atmosphere. Atmospheric accumulation of methane (CH_4) is one such gas which has increased from historic levels, as have many other greenhouse gasses. Table 1 (Houghton et al., 1990) lists this increase in greenhouse gasses.

This increase in methane is mainly anthropogenic in nature and is of concern primarily due to the potent influence methane has on global warming. Methane is a much more potent greenhouse gas than carbon dioxide on a molecule for molecule, or mass basis. Table 2 (IPCC, 1990) lists the relative radiative forcing potential for a number of currently and recently used greenhouse gasses compared to that of carbon dioxide. Table 3 lists the gasses that are expected to replace some of the ChloroFluoroCarbons (CFC's). CFC's are expected to be phased out by the year 2000 by the Montreal Protocol, an international agreement signed in 1987. In addition, the HydroChloroFluoroCarbons (HCFC's) that are expected to replace the CFC's will themselves be phased out by the year 2030 by the same international agreement. They are expected to be replaced by HydroFluoroCarbons (HFC's).

It is noteworthy that although the HCFC and CFC's are not as destructive to the ozone, it can be seen on Table 3 that they are strong greenhouse gasses.

The world temperature has been rising in the last century. This can be seen indirectly by the rising water levels of the oceans, (IPCC, 1990) and the retreat of alpine glaciers. The retreat of alpine glaciers is obvious to anyone who has done much hiking. This is shown in figure 1 (Houghton et al., 1990).

The recent rise of the world temperature is shown in figure 2 (Hansen, et al., 1989)

As the world population has increased, so has the amount of methane in the atmosphere. The world population has increased precipitously as seen in the Figure 3 (McEvedy, J., and R. Jones, 1978).

Just as the world human population has been increasing, so too has the world cattle population, as can be seen in figure 4 (Crutzen, et al., 1986, and McEvedy and Jones, 1978).

The population of other domesticated animals has also increased as seen in figure 5 (Lashof and Tirpak, 1990).

Table 1 Greenhouse Gasses Influenced by Human Activity

	CO2	CH4	CFC-11	CFC-12	NO2
Preindustrial Atmospheric Concentration	280 ppmv	0.8 ppmv	0	0	288 ppbv
Current Atmospheric concentration (1990)	353 ppmv	1.72 ppmv	380 pptv	484 pptv	310 ppbv
Current rate of annual atmospheric accumulation	1.8 ppmv	0.015 ppmv	9.5 pptv	17 pptv	0.8 ppbv
Rate of atmospheric accumulation by percent	0.50%	0.90%	4%	4%	0.25%
Atmospheric lifetime (years)	50-200	10	65	130	150

ppmv = parts per million by volume
ppbv = parts per billion by volume
pptv = parts per trillion by volume

The 1990 concentrations have been estimated on the basis of an extrapolation of measurements reported for earlier years, assuming that the recent trends remained approximately constant.

Net annual emissions of CO2 from the biosphere not affected by human activity, such as volcanic emissions, are assumed to be small. Estimates of human-induced emissions from the biosphere are controversial.

For each gas in the table, except CO2 , the "lifetime" is defined as the ratio of the atmospheric concentration to the total rate of removal. This time scale also characterizes the rate of adjustment of the atmospheric concentrations if the emission rates are changed abruptly. CO2 is a special case because it is merely circulated among various reservoirs (atmosphere, ocean, biota). The "lifetime" of CO2 given in the table is a rough indication of the time it would take for the CO2 concentration to adjust to changes in the emissions.

CFC represents ChloroFluoroCarbon

CFC-11, is released from insulation and CFC-12 is refrigerant 12 (Freon 12, a duPont trademark) a common domestic refrigerant.

Source: Intergovernmental Panel on Climate Change. 1990. Climate Change: The IPCC Scientific Assessment, J.T.Houghton, G.J.Jenkins, and J.N. Ephraums, eds., New York: Cambridge University Press

Table 2 Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) of Various Gasses in Current of Past Use

			Radiative Forcing Relative to Carbon Dioxide per Molecule Change and per Unit Mass Change in the Atmosphere for Present-Day Concentrations		Ozone Depletion Potential relative to CFC-11=1
			Change in Radiative Forcing (ΔF) Relative to Change in Temperature (ΔC)		
Gas		**Use**	Per Molecule relative to Carbon Dioxide(#1)	Per Unit Mass Relative to Carbon Dioxide(#1)	On a mass per mass basis (#3 & #4)
CO2			1	1	0
CH4			21	58	0
N2O			206	206	*
CFC-11	CCl3F	Insulation, refrigerant	12,400	3,970	1
CFC-113	CCl2FCClF2	Refrigerant, solvent	15,800	3,710	0.8
CFC-114	CClF2CClF2	Refrigerant, propellant	18,300	4,710	0.8
CFC-115	CClF2ClF3	Refrigerant, propellant	14,500	4,130	0.4
CCl4		solvent, chemical reagent	5,720	1,640	1.2
CH3CCl3			2,730	900	0.1
CF3Br	Halon 1301	Fire extinguisher	16,000	4,730	10
CCl2F2	"Freon 12"	Refrigerant		7,300 # 2	1
CHClF2	"Freon 22"	Refrigerant		1,500 # 2	0.05

CO2, CH4, and N2O are from 1990 concentrations.
CFC indicates ChloroFluoroCarbon
Freon is a trade name used by duPont
* N20 can destroy stratospheric ozone, but its ODP is undefined

(#3) Downing, 1988
(#4) Nelson and Wevill, 1989

Source: (#1) Intergovernmental Panel on Climate Change (1990).
(#2) Fischer, et al., 1992, the GWP listed by this source slightly different than that listed by #1, but comparison among those species listed by this source can be made.

Table 3 Global Warming Potential (GWP) and Ozone Depletion Potential (ODP) of Various Gasses Proposed as Possible CFC Substitutes

Gas		Use	GWP by molecule(#1)	GWP by mass(#1)	ODP (#2 & #3)
HCFC-123	CHCl2CF3	Aerosol Propellant, Refrigerant	9,940	2,860	0.02
HCFC-124	CHClFCF3	Aerosol Propellant	10,800	3,480	0.02
HFC-125	CHF2CF3	Aerosol Propellant	13,400	4,920	0
HFC-134a	CH2FCF3	Aerosol Propellant, Refrigerant	9,570	4,130	0
HCFC-141b	CH3CClF2	Refrigerant	7,710	2,900	0.1
HCFC-142b	CH3CClF2		10,200	4,470	0.06
HFC-143a			7,830	4,100	0
HFC-152a			6,590	4,390	0

CFC indicates ChloroFluoroCarbon
HCFC indicates HydroChloroFluoroCarbon, which as a class is less stable than CFC's
HFC indicates HydroFluoroCarbons, which carry no Chlorine or Bromine and are ozone "friendly"
GWP indicates Global Warming Potential, using CO2 for comparison
Freon is a trade name used by duPont
ODP indicates Ozone Depletion Potential, Using CFC-11 for comparison
Source: (#1) Intergovernmental Panel on Climate Change (1990).
(#2) Downing, 1988
(#3) Nelson and Wevill, 1989

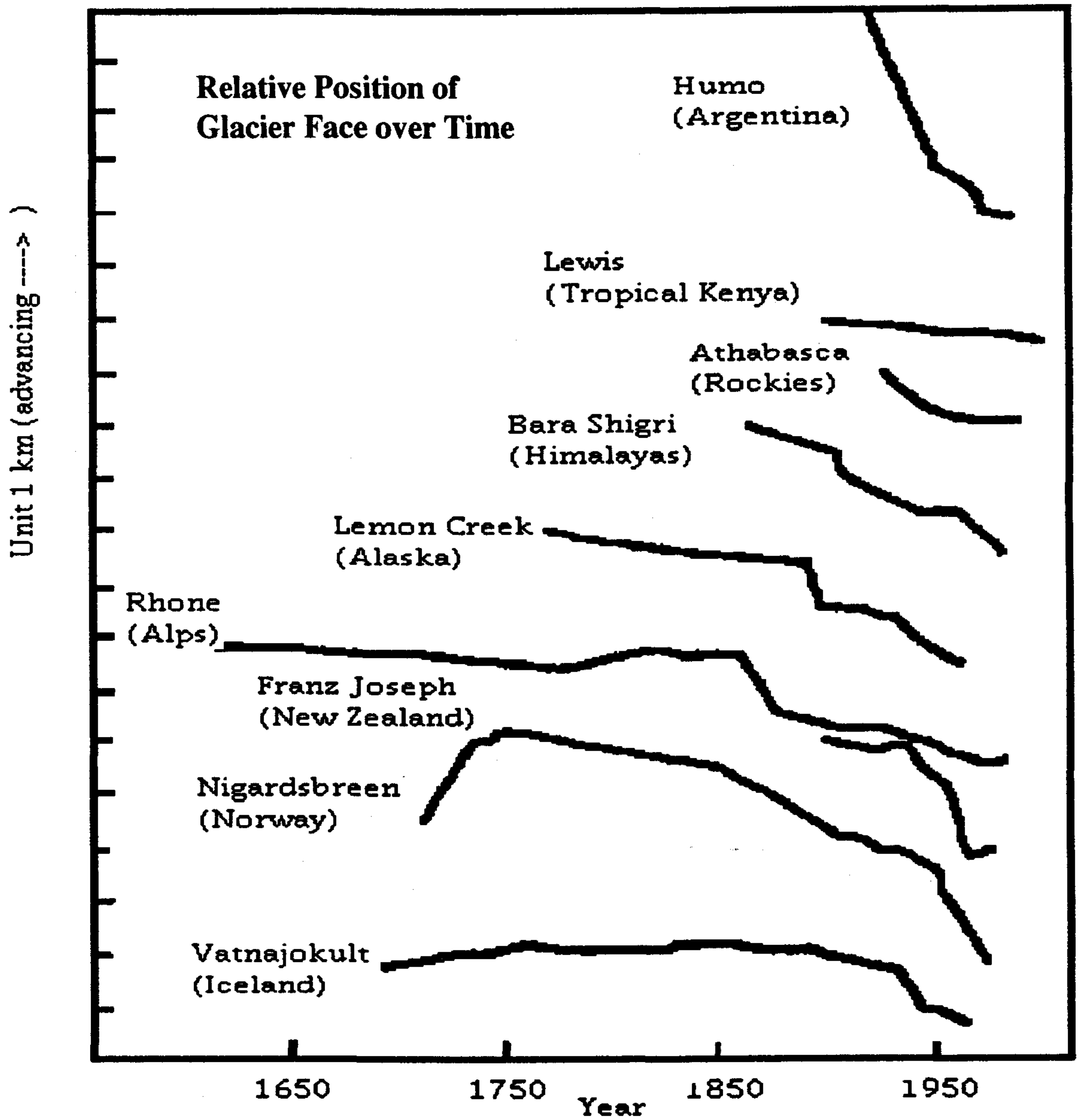
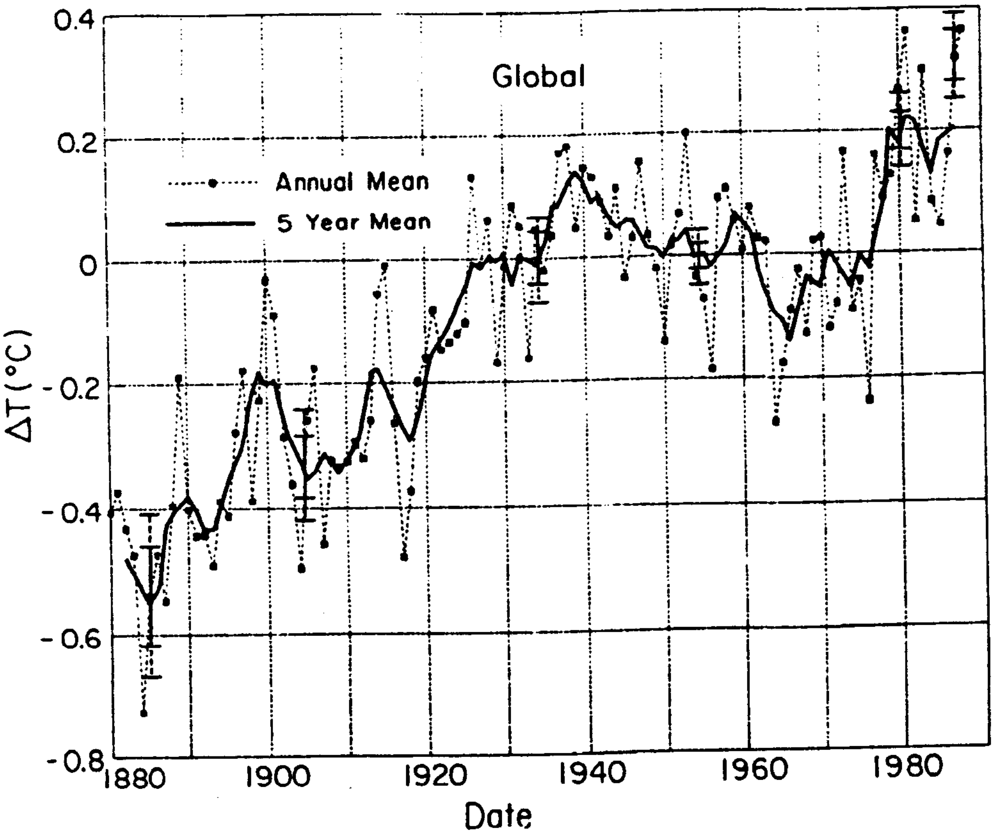


Figure 1 Relative Position of Glacier Face Over Time
(Houghton et al., 1990)



Global surface air temperature change estimated from meteorological station data. Uncertainty bars (Hansen and Lefedeff, 1988) account only for the incomplete spatial coverage of the stations. The error bar for 1988 is larger than that indicated for 1987 because of poorer station coverage and approximations in the near-real-time data used for the last several months of the year. Note also that no correction has been made in this figure for urban warming, which is estimated as 0.1-0.2° C for the century.

Figure 2 Global Annual Mean Temperature Over Time
(Hansen, et al., 1989)

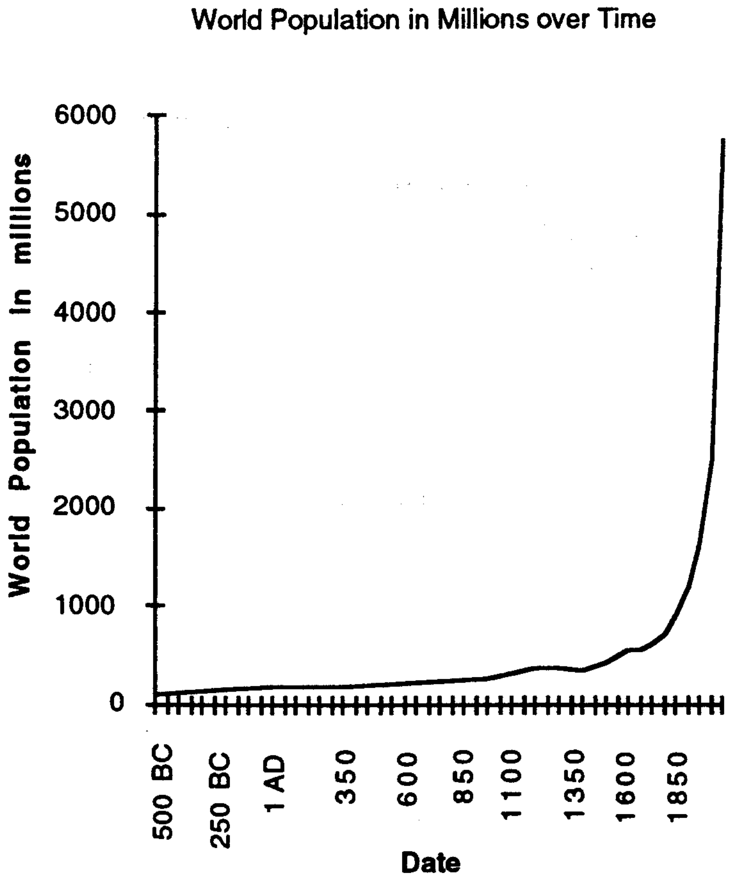


Figure extrapolated to the year 2000 with 5,750,000,000 people.

Figure 3 World Population Over Time

(Data from McEvedy, J., and R. Jones 1978)

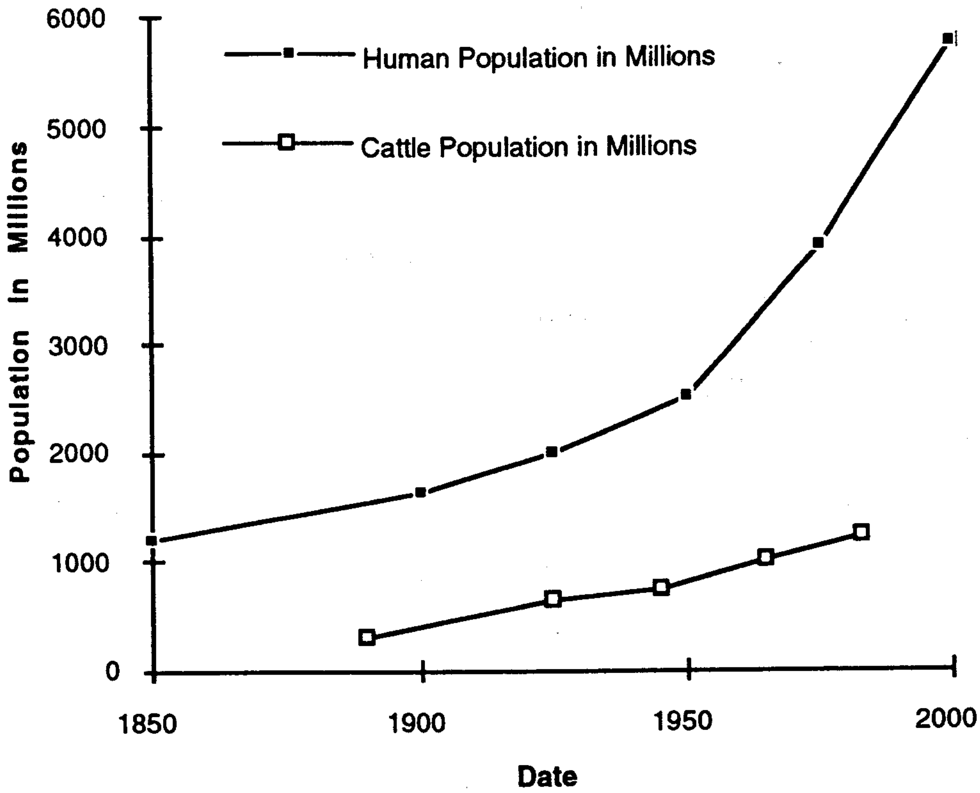


Figure 4 Human and Cattle Population Over Time

Source of data : Crutzen, et al., 1986, (cattle population) and McEvedy and Jones, 1978 (human population)

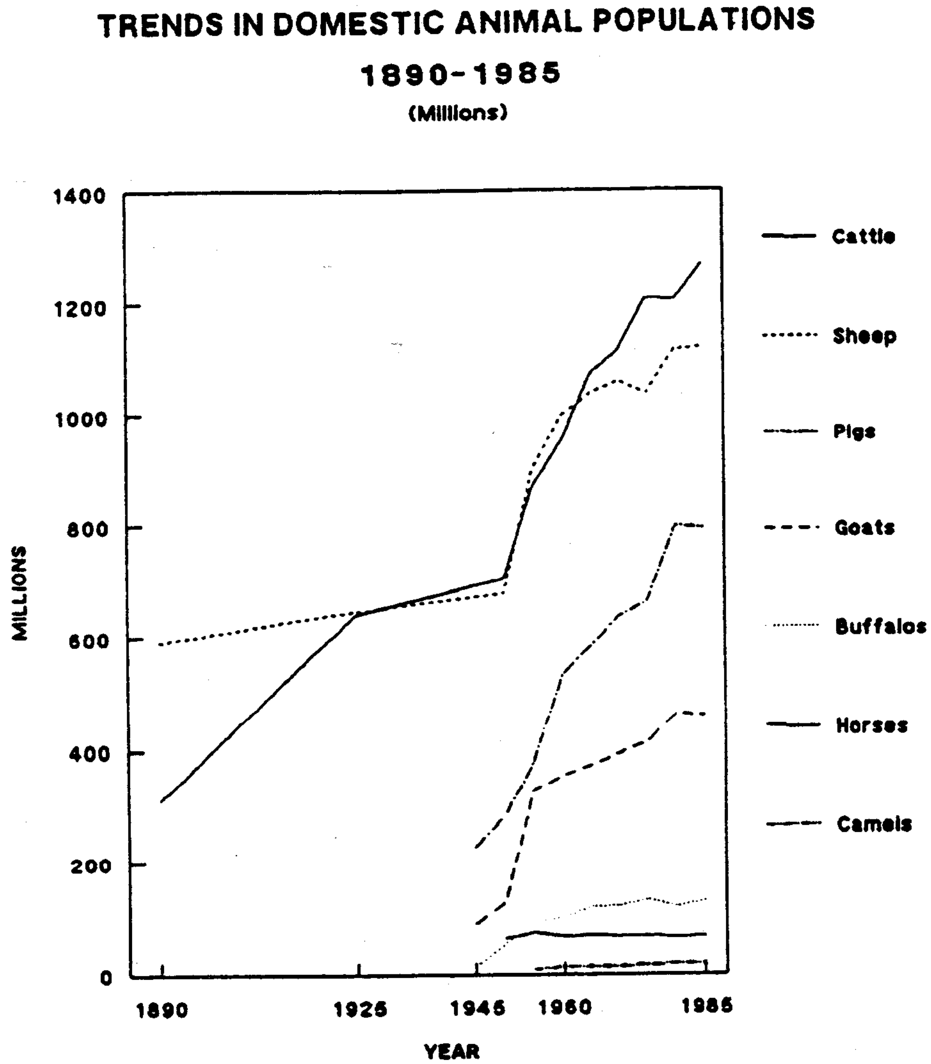


Figure 5 Trends in Domestic Animal PopulationS
Source: Lashof and Tirpak, (1990)

It might appear that humans themselves might be the main contributors of atmospheric methane, and they are, but due to the activities of humans and not the presence of humans themselves. Crutzen, et al, 1986 estimated the emissions due to domesticated ruminants as 74 Tg of methane/year. Wild ruminants contribute another 2-6 Tg methane/year while humans contribute less than one Tg methane per year. These estimates virtually ignore potential methane release from manure (Patterson, 1989). Casada and Safley (1990) estimated the amount of methane produced from manure by making certain assumptions about the percentage of ultimate methane yield (Bo, in m^3 CH_4/kg-VS) that could be expected by different animal waste management systems.

Methane (CH_4) is formed in nature by the anaerobic bacterial decomposition of organic matter. For years it was considered a two step process where facultative organisms hydrolyze complex organic matter and form organic acids by way of the glycolytic pathway and Krebs TCA cycle. Methanogens then form methane by the following two reaction pathways.

1) CH_3COOH (acetate) --> $CH_4 + CO_2$

2) $4\ H_2 + CO_2$ --> $CH_4 + H_2O$

Methanogens were thought to ferment alcohols and fatty acids to methane. It now appears that there is a more complex overall process of anaerobic digestion that requires an interaction between the fermentative bacteria and the methanogenic bacteria. The anaerobic digestion of manure represents a delicately balanced ecological system in which a heterogeneous population of bacteria play a role. "The overall process of anaerobic digestion requires an interaction between the fermentative bacteria and the methanogenic bacteria that is more complex than the simple sequential metabolism originally envisioned. This relationship is based on interspecies hydrogen transfer..."(Gaudy, 1988). The removal of hydrogen as shown in reaction 2) above, pulls the reaction forming the hydrogen to completion. This reaction happens to be the formation of acetyl-CoA. "Thus amino acids, fatty acids, and other compounds that are metabolized to acetyl-CoA in aerobic systems but not in anaerobic pure cultures can be fermented to acetate and hydrogen, yielding energy for the fermentative organism and hydrogen (and acetate) for use in methane formation" (Gaudy, 1988). Bo is the ultimate methane potential of a material that is anaerobically digested. Some sources refer to this as the Biologic Methane Potential (BMP). Material is placed in a serum bottle with a mixed culture anaerobic methanogenic inoculum and fermented anaerobically. The methane produced by the material divided by the amount of volatile solids of the material is its Bo. The percentage of ultimate Bo that is achieved by differing manure management practices was called its Methane Conversion Factor (MCF). A number of waste management systems were evaluated. The defining characteristic of the various waste management systems are outlined on tables 4, 5, and 6. This study was done to evaluate Casada and Safley's assumptions of MCF for differing waste management systems. Casada and Safley's assumptions of MCF are shown on table 7 and table 8.

Table 4 Waste Management Systems Definitions for Pasture/Range/Feedlot/Drylot

From Safley, et al., 1992 with explanations of how waste management systems were approximated in this study

A variety of waste management practices are in use throughout the world. In many parts of the world, manure is spread on the fields as a fertilizer. In other cases, manure is used as an energy source. The following is a brief description of the major animal waste management systems in use.

Pasture/Range	Animals that are grazing on pasture are not on any true waste handling system. The manure from these animals is allowed to lie as is and is not handled at all. This was approximated by manure incubated in an open incubator. The specimen was kept open for 6 days and then covered on the seventh day. The evolved gasses were collected during the seventh day. The results were multiplied by seven to approximated the amount of gasses produced over the entire week period. Gas collection continued for 150 days in the last three studies and total amount of gas collected during that period was summed.
Feedlot/Drylot	In dry climates feedlot animals may be kept on unpaved feedlots where the manure is allowed to dry on the feedlot and is periodically removed. This manure is subject to about the same limited conditions for methane production as that on pasture. Because this waste management treatment is so similar to Pasture/Range, the method used to approximate it was the same as that used for Pasture/Range.

Table 5 Waste Management Systems Definitions for Solid Storage/Liquid Slurry

From Safley, et al., 1992 with explanations of how waste management systems were approximated in this study

Solid Storage	In a solid storage system the solid manure is collected just as in the daily spread system, but this collected manure is stored in bulk for a long period of time (months) before disposal. Safley, et al., considered the manure in this system to have about the same methane producing potential as manure lying on pasture. This study considered them to be different in that Solid Storage had less drying and less exposure to the atmosphere. Solid Storage was approximated in this study by manure placed into incubator that were kept sealed for the entire week gas collection period and all evolved gasses during that time capture and measured for volume and quality.
Liquid/Slurry Storage	Water usually must be added to the manure, reducing its total solids concentration to less than 12% for liquid systems. Slurry systems may or may not require additional water. When the resulting liquid or slurry is stored the increased opportunities for anaerobic conditions will lead to methane production from anaerobic digestion. When the storage facility is sufficiently deep the conditions may be almost entirely anaerobic, thereby maximizing the methane production potential of the manure. For these systems temperature may be the process limiting factor. This waste management system was approximated by adding water to manure to make a slurry. The slurry was added to the incubator and sealed closed for the weeklong gas collection period. All evolved gasses during that time were captured and measured for volume and quality.

Table 6 Waste Management Systems Definitions for Daily Spread/Anaerobic Lagoon From Safley, et al., 1992 with explanations of how waste management systems were approximated in this study

Daily Spread	In the daily spread system, manure was collected from the feedlot in solid form with or without bedding, by some means such as scraping. The collected manure was then hauled to crop producing fields on a regular basis (usually daily) and spread on these fields. The spreading process speeds up the drying of the manure, as compared to drying on pasture, and drastically limits the methane producing potential. This waste treatment system was not directly approximated in this study but was evaluated indirectly by inference to results in the Feedlot/Drylot systems.
Anaerobic Lagoon	In a liquid manure handling system the manure may be put in a deep lagoon (greater than 6 feet) specifically designed to create anaerobic conditions as the means of treating the waste. Typically, almost all of the methane production potential of the waste will be realized in the anaerobic lagoon, assuming appropriate loading rates. It is possible to cover these lagoons and harvest methane gas that is evolved for its energy potential. Roos, 1992 reports anaerobic lagoons have a total solids content of something less than 2%. Safley, et al., estimate an Methane Conversion Factor (MCF) of 90% based on their extensive knowledge of such systems. This waste treatment system was not directly approximated in this study but was evaluated indirectly by inference to results other systems.

Table 7 U.S. Methane Emissions from Waste Management Systems

System Type	MCF	source
Pasture/Range	10%	2
Anaerobic Lagoon	90%	1
Liquid/Slurry Storage	20%	1
Drylot	10%	2
Solid Storage	10%	1
Daily Spread	5%	1

1 Casada and Safley, 1990
2 Yancun et al., 1985
3 Chen et al., 1988

Table 8 Worldwide Animal Waste Management Systems

System Type	MCF	source
Pasture/Range (arid/semiarid region)	5%	1
Anaerobic digester	5%	1
Anaerobic digester (Chinese design)	14%	2
Burned for fuel (Moist region)	10%	3
Burned for fuel (arid/semiarid region)	5%	1
Incineration	5%	1
Compost	0%	1

1 Casada and Safley, 1990
2 Yancun et al., 1985
3 Chen et al., 1988

Casada and Safley then used these assumptions of MCF along with worldwide population of various animals, enumerated by various animals and country, typical Bo values for each animal group and for each country, to estimate the total worldwide production of methane from manure. Casada and Safley's results are shown on table 9.

Cicerone and Oremland (1988) enumerated the worldwide emission of methane into the atmosphere per year. Their results, adjusted for the additional 28.4 Tg/yr estimated by Casada and Safley are shown on table 10 and figure 6. Figure 6 shows that methane generated from manure accounts for about five per cent of the global methane budget.

Methane is a potent greenhouse gas as seen be its relative greenhouse effect compared to carbon dioxide. As seen on Table 2, methane has 58 times the greenhouse warming effect as carbon dioxide, on a mass basis. Figure 7 and 8, shows the relative effect of a number of greenhouse gasses on green house warming (Ramanathan et al., 1985 and Hansen et al., 1988). These two studies however, neglect the atmospheric residence times of the various greenhouse gasses. Lashof and Ahuja (1990) proposed an alternative weighting index that takes atmospheric residence time into account. Using an arguable atmospheric lifetime of 100 years for carbon dioxide and 10 years for methane, Lashof and Ahuja developed the relationships shown in figure 9. They show that carbon dioxide (including carbon dioxide originating as carbon monoxide) contributes 78.2% of the global warming potential of current greenhouse gas emissions. Methane only contributes 9.2% of the global warming potential. Using Casada and Safley's estimate of methane produced from manure, methane contributes 5% of the total methane budget as seen in figure 6. In other words, manure is responsible for 5% of 9.2% (or 0.46%) of the greenhouse effect. Theoretical and numerical analyses agree that the increase of greenhouse gasses (due primarily to the burning of fossil fuels) in the atmosphere will cause a warming of the global average temperature of 1.4° to 4.5° C during the 21st century (Taylor and MacCracken, 1990). Thus if manure fermentation is responsible for 0.46% of this effect, then manure fermentation is responsible for between 0.006 and 0.021° C rise in global average temperature. This amount is small enough to be considered inconsequential.

The question remains about how good Casada and Safley's estimates were regarding the amount of methane that could be expected to be generated from manure. If their estimate was substantially low, then a higher amount of temperature change due to methane could be expected. This study was done to evaluate the accuracy of Casada and Safley's estimated methane conversion factors, and ultimately the amount of methane that they calculated to be generated from manure.

Table 9 Worldwide Methane Emissions from Animal Waste

Animal Type	Million Head	Methane, Tg/yr
Cattle (non-dairy)	1049	9.5
Dairy Cattle	223	5.9
Swine	823	5.8
Sheep	1173	1.9
Goats	521	0.7
Poultry	10967	1.7
Buffaloes	137	0.5
Horses, Mules, Donkeys	122	2.2
Camels	19	0.2
Total		28.4 Tg/yr

Source: Casada and Safley, 1990

Table 10 Sources of Methane

Annual emissions of methane into the atmosphere in Teragrams (10^12 grams or millions of metric tons)

Source	Quantity	Percent of Total
Natural Wetlands (Including bogs, swamps tundras)	115	20.4%
Rice Paddies	110	19.5%
Enteric Fermentation (ruminant animals)	80	14.2%
Biomass Burning (includes fuel weed, agricultural burning, forest fires)	55	9.8%
Gas Drilling, Venting, Transmission	45	8.0%
Termites	40	7.1%
Landfills	40	7.1%
Coal Mining	35	6.2%
Oceans	10	1.8%
Fresh Waters	5	0.9%
Animal Manure (all types, cattle, swine, sheep, goats, poultry, buffalo, horses, camels)	28	5.0%
Total	563	

Source: Cicerone and Oremland (1988) adjusted for methane from manners, proposed by Casada and Safley (1990)

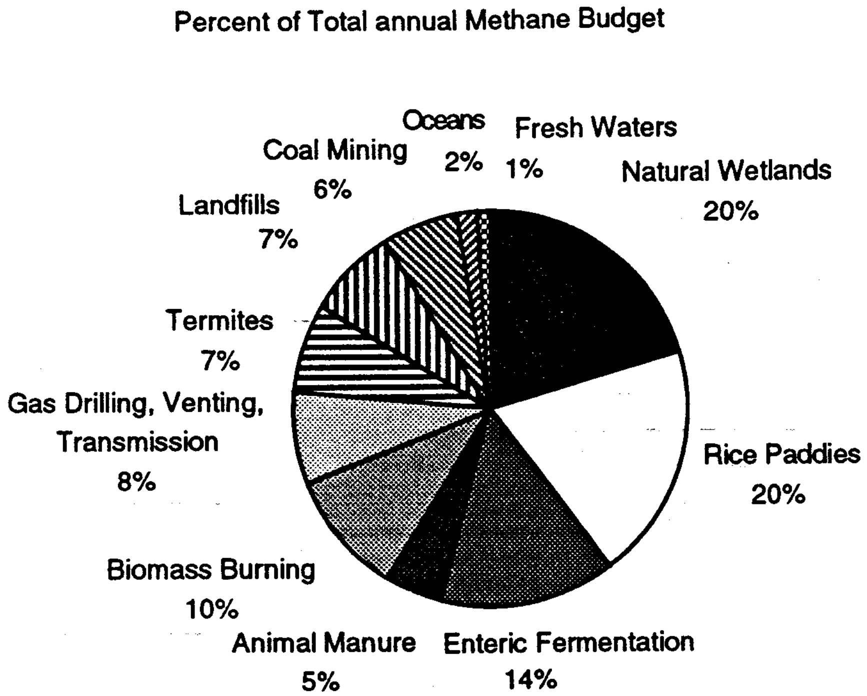


Figure 6 Source of Annual Global Methane Budget
Source: Cicerone and Oremland (1988) adjusted for methane from manures, proposed by Casada and Safley (1990)

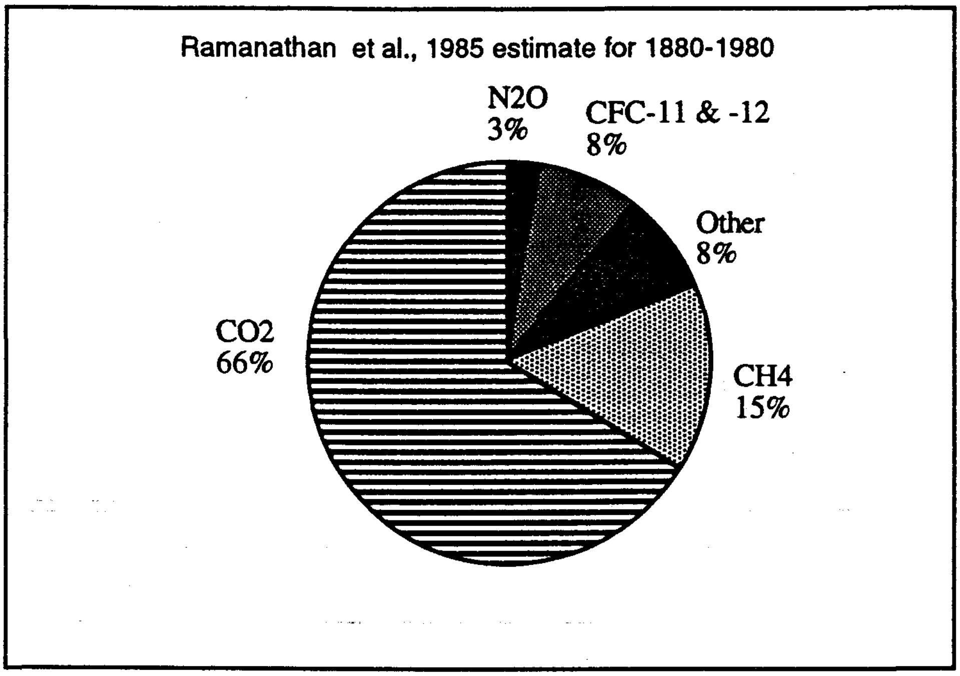


Figure 7 Relative Historic Contributors to Global Warming
Source: Ramanathan, et al., 1985

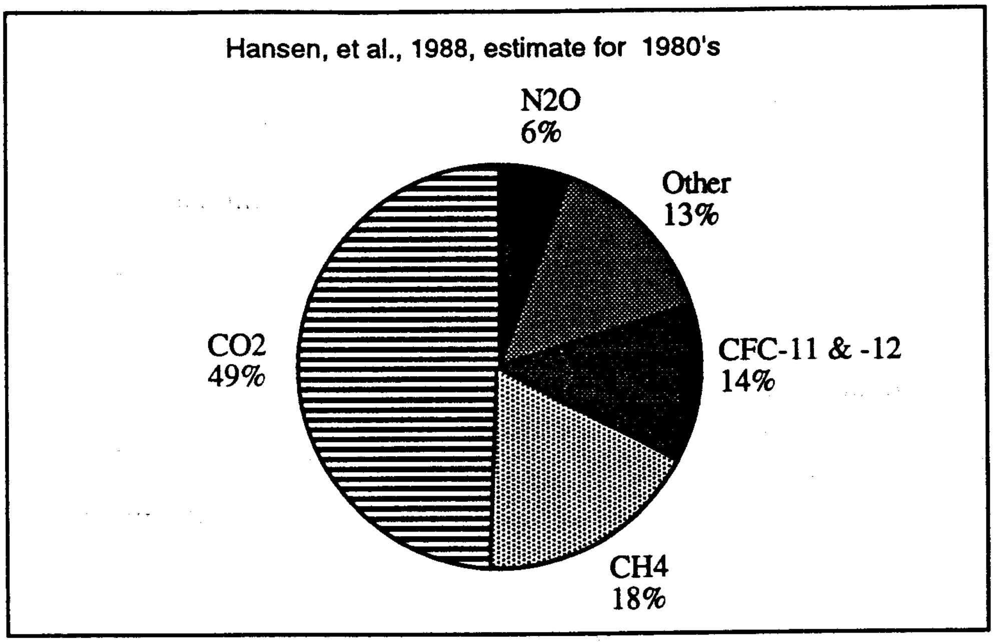


Figure 8 Relative Recent Contributors to Global Warming
Source: Hansen, et al., 1988

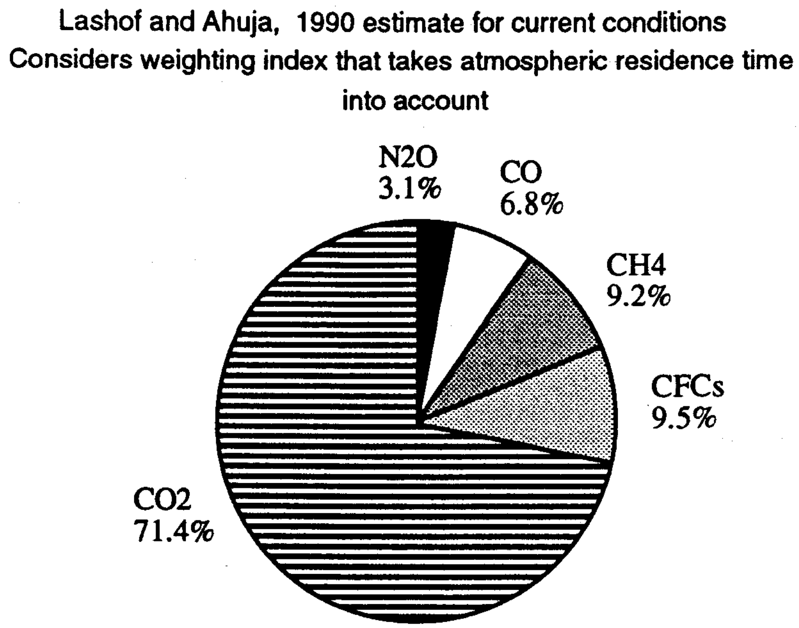


Figure 9 Relative Recent Contributors to Global Warming, Revised for Global Lifetimes of Greenhouse Gasses
Source: Lashof and Ahuja, 1990

Materials and Methods

Treatments

The trials can be distinguished from each other primarily on the basis of temperature. Each trial had a number of different waste management treatment simulations. They are outlined on Table 11.

Table 11 Waste Management Simulations for Trials

	Trial 1, 20° Manure and Straw	Trial 2, 30° C Manure	Trial 3, 20° C Manure	Trial 4, 10° C Manure
Feedlot(closed)	X	X	X	X
Feedlot(open)	X	X	X	X
Pasture (closed)	X	X		
Pasture(open)	X	X		
Slurry(closed)	X	X	X	X
Slurry(open)	X	X	X	X
Slurry and Inoculum(closed)		X	X	X
Slurry and Inoculum(open)		X	X	X
Slurry(open) with replenishment			X	X
Slurry and Inoculum(open) with replenishment			X	X

* With replenishment means aged water was added to sample weekly to maintain hydration. Aged water is water that has remained open to the atmosphere for a week, to dissipate chlorine.

* With inoculum means a culture of methanogenic bacteria was added to the sample. Inoculum came originally from an anaerobic digestor at a waste treatment plant. This was then acclimated to dairy cattle manure by being fed dairy cattle manure periodically and exclusively over a period of several years.

*Closed means the incubator was kept closed for the entire weeklong collection period.

*Open mean the incubator was open for six days of the collection period and then closed and the gas collected on the seventh day. Results multiplied by seven to obtain weeklong gas production.

Manure

The manure that was used came from dairy cows (Holsteins, Bovis sp.) fed a high energy diet of 58% corn silage, 12% alfalfa hay, 6% cotton seed, and 24% grain (a concentrate of corn and pelleted feed mix). Due to the high energy diet, the manure was extremely loose and would not "stack." In order to get the manure stiff enough to form a conical shaped pile (for the "pasture" treatment), straw, (annual ryegrass, Lolium temulentum) was added as a thickener, for the first trial samples (manure and straw at 20° C). To keep these waste management system simulations uniform, straw was added to all the test samples. We wanted the slurry to have 8-10% dry solids. Previous studies showed the manure to be about 14% dry solids. Therefore it was calculated that 65% manure and 35% water would yield a 9.1% dry solids mix. Unfortunately when 5 kg of manure was mixed with 2.690 L of water, and 100 gms of straw, the straw brought the dry solids back up to approach normal levels for manure. The analysis of the manure, straw, water and mixture for percent dry solids and percent volatile solids were done after the actual start of the incubation period, so fine adjustment of percent dried weight was impossible. The idea behind the straw was that it would help mimic natural conditions but the use of the straw introduced a number of new variables. The straw was a fermentable substrate as was later demonstrated when water was added. A known weight of straw was placed into a graduated cylinder and a known volume of water was added. The straw was allowed to sit, and 8 hours later demonstrated rapid bacterial action as evidenced by effervescence.

Later trials (30°, 20° and 10° trials) were completed using manure collected at one point in time, with no straw added. A large amount of manure was collected and thoroughly mixed with a plaster mixer connected to a motor. The manure was then divided into 5 kg aliquots. Some of the manure was used fresh for the next starting trial (30° C manure), and the rest of the manure was frozen at -15° C for use in the later trials (20° C manure, and 10° C manure trials). Straw was not added to these later three trials because of the lack of success achieved in using straw in the preliminary trial. In the preliminary trial, manure with straw, the manure was very plastic. Even though it did originally maintain a conical shape for the initial "pasture, stacked pile" simulation, over the time of the trial it collapsed down to a flat oval, and achieved similar results to the feedlot simulation, which was a flat oval. An attempt part way through the first trial using freshly collected manure and straw placed in a conical shaped screen form was also unsuccessful for the same reason.

Apparatus

In all four trials, the waste material was incubated in a 26.7 cm bottom diameter to 29.2 cm top diameter by 38.1 cm high, high density polyethylene sealable container. A black polyethylene male connector with pipe thread and 0.48 cm hose barb was mounted firmly to the container's lid with a 1.9 x 1.3 cm nylon reducer bushing. The above plastics were obtained from Consolidated Plastics Company, Inc., Twinsburg, Ohio. A sure seal was achieved by use of a silicon sealant. The sealant was allowed to dry thoroughly before starting each trial to prevent pH change due to the acetic acid evolved in the drying process. Figure 10 shows a schematic of the incubation vessel.

A new lid was used at the beginning of each trial to ensure against wear created gas leaks in the system. A heavy 0.48 cm ID rubber hose was connected to the incubator container and the other end was connected to a 61 by 61 cm 4 mil duPont Tedlar gas collection bag (Pollution Control Corp., Oak Park, IL). The Tedlar bags were inspected regularly and any leaks patched with Tedlar tape.

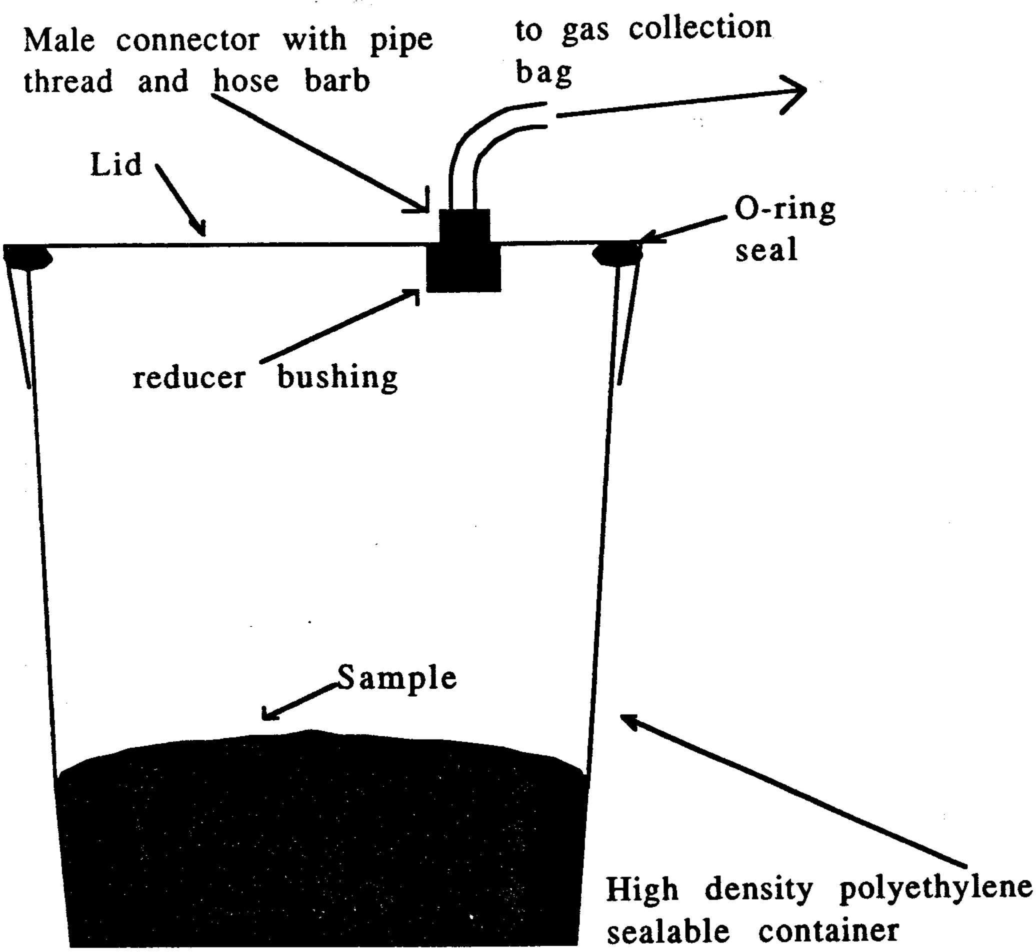


Figure 10, Incubator Schematics

Gas Measurement Apparatus

A large syringe was used to measure the volume of gas produced. The syringe was constructed from a 1000 ml graduated cylinder with a #12 (67mm top diameter, 56 mm bottom diameter, 52 mm thick) black rubber stopper attached to a metal rod as a plunger. A hole was drilled in the bottom of the graduated cylinder and a nipple and rubber tubing were attached. The 1000 ml graduated cylinder syringe was tested for volumetric delivery using water and another graduated cylinder. Its delivery volume was found to be exact. Heavy black rubber tubing was attached by way of a tee, to a 140 ml syringe and the bag with the gas to be measured. The 140 ml syringe not only adds additional volume to the gas measuring apparatus, but also was much more sensitive to pressure differences from atmospheric, allowing its plunger to equilibrate to atmospheric pressure. This method has the advantage of giving a rapid, accurate, directly observable gas volume measurement.

Trial 1

The first trial was set up to be run at 20° C. Twelve incubation containers were set up. Duplicate runs were done simulating feedlot, pasture, and slurry manure management. These six runs were conducted with the incubators covered and the generated gasses continuously collected and measured for volume and quality (% CO2 and % methane). Six more incubation containers were similarly set up but were left uncovered to more closely mimic "natural conditions". These last six were covered once a week for 24 hours and the gasses generated during this time period measured for volume and composition. In this way we could simulate normal waste management conditions found in practice, and get baseline methane emission values with which to compare other studies that use alternate treatment methods. Five kg of manure and 100 g of straw were used in each run of this trial. The slurry contained 5 kg of manure, 100 g of straw and 2.777 kg of water. This amount of water was chosen (in an attempt) to bring the original 14% total solids of the manure to 9% total solids of a slurry. Large weights such as the 5 kg samples were weighed on an Ohaus (max 22.1 kg) beam balance.

Trial 2

The 30° C trial was started with duplicate runs simulating feedlot, slurry, and slurry with inoculum. The manure for this trial and all further trials was collected at this time. The manure was used fresh for this trial and frozen in 5 kg aliquots for the succeeding trials. These runs were run both with the lids on for the entire week period, and another set with the lids off for six days and then closed and the gas collected on the seventh day. Methane generated from this second set, with lids off for six days and lid on for one day, was calculated by multiplying the amount of gas generated by a conversion factor (usually about 7) to convert to an entire weekly collection equivalent period.

A waste management system that incorporated a methanogenic bacterial inoculum was started with this and continued through all succeeding trials. The inoculum treatment was added because in practice, slurry tanks are not cleaned and some inoculum is present when it is filled. We wanted to see if the presence of inoculum would affect the Methane Conversion Factor (MCF).

The inoculum used in this trial came from a methanogenic bacterial culture maintained at 50-55° C in numerous (6-9) 3 L glass carboys. The inoculum culture was kept in suspension by shaking on a G10 Gyrotary Shaker at 120 RPM. The rotator was manufactured by New Brunswick Scientific Co., Inc. Edison, N.J.. The original bacterial culture came from an anaerobic digester at a sanitary waste treatment plant. It was fed with dairy cow manure on a regular basis and consequently became acclimated to dairy cow manure. The culture was not fed for 6 weeks prior to using as inoculum for these runs and for the concomitant Bo determinations. This was done to reduce the amount of fermentable material added with the inoculum.

No straw was added in this (30° C) trial and the pasture conical piles were not attempted due to lack of success during the 20° trial with straw. As before, 5 kg of manure was used in each run (feedlot open, feedlot closed, slurry open, slurry closed, slurry with inoculum open, slurry with inoculum closed, all in duplicate). As before the slurry had 2.777 kg of water added. The slurry with inoculum had an additional 1.9944 kg of inoculum added. This ratio was used to be consistent with the earlier 20° C manure with straw trial and the inoculum amount was chosen to give an arbitrary 1:5 mix (4 parts slurry to 1 part inoculum).

Trial 3 and 4

The later two trials were set up identically. They were run at 20° C and 10° C respectively. They had runs consisting of feedlot, slurry, and slurry with inoculum (all both open and closed). In addition a set of runs were completed consisting of slurry and slurry with inoculum, both open for the entire 6 days and the gas collected the seventh day. The difference was that these runs had water added back to compensate for evaporation.

Ultimate Methane Yields

At the beginning of all four of these trials, a sample was taken from a representative manure sample for determining the Bo (ultimate amount of methane (mls) per gram volatile solids, sometimes known as the Biologic Methane Potential (BMP)). This was done in triplicate for the first two trials. For the later two trials the most and least desiccated samples were chosen and also run in triplicate to determine the Bo. No real difference was seen in these samples, so the results of the six replicates were averaged. At the end of each trial, the Bo of the residue was also determined, again with six replicates.

Bo determination was done according to the procedure developed and used by Hashimoto (1989). Serum bottles served as fermentors. Each fermentor had an effective volume of 119 mls but were rated and sold as 100 ml serum bottles by Fisher Scientific. The serum bottles were sealed with 1 cm thick black butyl rubber stoppers (Bellco Glass, Bineland, New Jersey). The black butyl rubber stopper was secured with a 20 mm tear off aluminum serum bottle seal (Wheaton Scientific, Millville New Jersey). Gas production and constituent analyses were performed throughout the fermentation period. Gas volume was measured by using glass syringe with a number 20 gauge, one inch long needle. The glass bore was wetted and the needle inserted through the black rubber stopper in the serum bottle. The pressure that was created by the fermentation process expelled the glass plunger on the horizontally held syringe until room pressure was achieved. The volume was read from the syringe. 10, 30 50 and 100 ml glass syringes were used. On occasion, more than 100 mls of gas was produced in one collection period. When this occurred, more than one syringe was inserted into the serum bottle simultaneously, so that all syringes contained the gas at the current atmospheric pressure. In a similar manner, the gas sample was taken from each bottle with a 0.5 ml gas syringe fitted with a Fisher Scientific Series A, Gas Side Port Needle. 0.2 ml were then injected into the calibrated HP 5890 GC to determine the quality.

For the 20° C manure and straw trial, 25 gm of wet manure and 50 gm of the previously described inoculum were placed in the serum bottle, purged of oxygen by bubbling nitrogen gas through the sample. The bottles were then sealed and incubated at 35° C. The residual Bo studies were performed similarly. The ratio of 2:1 inoculum to substrate ratio was used as recommended by Hashimoto (1989). Hashimoto's recommendation was on a volatile solids basis and this study ratio was on a mass basis (effectively a volume per volume basis), but volatile solids amount was unknown until after the Bo studies were set up. However the 2:1 inoculum to substrate ratio was much higher than the limiting ratio of 0.25:1, for a comfortable margin of error.

For the later studies, only 15 gm of wet manure or 2 gm of dried manure and 13 gm of water were combined with 50 gm of inoculum. This change was introduced to reduce the amount of gas produced in each serum bottle to more manageable levels. The higher amount of material produced so much gas as to exceed the volume of the glass syringes used to measure the amount of gas produced. Also the smaller sample size created more head room, allowing for easier needle insertion for measurement of the amount of gas produced.

In all cases, inoculum samples (with no manure added) were also incubated to account for the amount of gas that was produced by the inoculum alone. This gas volume of methane was then subtracted out in later calculations for mls of methane produced for each sample.

Analytical Method

Samples were analyzed in triplicate for percent dry weight, percent ash, and by the difference for percent volatile solids. The manure was placed in tared crucibles and weighed on a Mettler H80 Balance (max 160 g) or a Mettler P1200 (max 1200g) balance. Both balances gave consistent readings but the Mettler P1200 was required when larger sample sizes were used. Results with both large and small sample sizes were consistent. The procedure used was that listed (Standard Methods for the Examination of Water and Wastewater, 17th Edition, 1989). The manure tended to hold moisture and required 48-72 hours of drying at 105° C. The samples also required longer than expected incineration times and temperatures to fully ash. The samples were incinerated in an incinerator (Lab-Heat Muffle Furnace, Blue M Electric Co., Blue Island, Illinois) that gradually increased in temperature to 600 degrees Fahrenheit over a period of 6 to 8 hours. A Thermolyne 62700 Furnace was also used for ashing samples and it gave comparable results. The dried samples were milled through a fine screen (1 mm diameter) in a Wiley Mill, and then analyzed for total carbon by the Biological Oceanography Department at Oregon State University. The sample was combusted and the carbon separation was performed on a Carlo Erba Instruments NA 1500 CN analyzer, a traditional analyzer for geochemistry. The analyzer was connected to an Hewlett Packard HP3396 Integrator for data analysis and printout.

Methane yield for both the initial Bo, and the residual Bo for the various treatment and temperature regimens were calculated as follows. The gas volume was measured by inserting the needle of a distilled water lubricated glass syringe directly into the serum bottles. Displacement of the glass plunger, which was positioned horizontally, was used as a measure of the gas production at the current atmospheric pressure. Gas production was corrected to standard temperature (0° C), and pressure (1013.25 millibars).

Methane and Carbon dioxide concentrations were determined with the HP 5890 GC equipped with a thermal conductivity detector. A Chromosorb 102 packed column was used. Helium was used as the carrier gas a flow rate of 18.6 to 19 ml/min. The temperatures of the injector, column, and detector were 100, 70, and 130° C respectively. The GC was calibrated with a number of calibration gasses (#1 5.17% CH_4/4.93% CO_2/89.9% N_2, #2 70.3% CH_4/29.7% CO_2, #3 30.8% CH_4/69.2% CO_2, and #4 51.8% CH_4/48.2% CO_2). The GC maintained its calibration fairly well for long periods but occasionally needed recalibration. The calibration was checked with each use by running all calibration gasses before starting samples and by rerunning calibration gasses periodically during the sample run. The oven temperature for the column was maintained at 70° C for sample analysis, but was raised to 200° C prior to and after each weekly run to purge moisture. The injector temperature was maintained at 100° C and the detector temperature was maintained at 130° C. The detector was turned on before each run at 70°C and then turned off after the 200° C bakeout period to preserve the life of the oxygen sensitive element in the detector.

In an analogous procedure, the volume and the quality of the gas evolved in the fermentation incubators was determined. The gas volume was calculated by drawing the gas out of the Tedlar gas collection bag with the 1000 ml syringe. The head space in the incubators was calculated by the difference in total volume of the incubator and the volume of the specimen that remained. The weight of the specimen remaining was calculated from the difference between the incubator tare weight and the current weight. The specimen weight was then used along with the assumption that the density of manure was about one gram per cubic centimeter to determine the specimen volume. This assumption was checked and proved to be valid.

The quality of the incubator sample gas was determined as follows. A gas sample was drawn off of each sealed container by puncturing the thick black rubber tubing with a gas syringe. It was felt that leaks would not develop through the puncture sites because of the low (near ambient) pressures experienced in these trials. The puncture ends of the tubing were cut off and discarded on a regular basis. The syringe was actually able to draw gas directly from inside the incubators, for a truly representative sample. The gas was sampled for quality at weekly intervals. Gas samples were analyzed, as described in the previous paragraph.

Methane yield for both the initial Bo, the residual Bo, and the various treatment and temperature regimens were calculated similarly. The gas expressed during each collection was multiplied by the methane fraction and the current standard temperature and pressure conversion factor. The amount of methane generated due to any added inoculum was then subtracted out. This was divided by the volatile solids used in each case. The total mls methane produced per gram volatile solids was then calculated by cumulatively adding the individual collections over time. These calculations were expedited by use of the Microsoft Corp. spreadsheet Excel 3.0, and later 4.0 for the Macintosh.

Results

Mass Balance Calculations

The following mass balance was performed

$$C_{Initial} = C_{remaining} + C_{CO_2} + C_{CH_4}$$

where $C_{initial}$ is the initial amount of carbon in the specimen, $C_{remaining}$ is the carbon in the specimen at the end of the incubation period, and C_{CO2} and C_{CH4} are the carbon from the carbon dioxide and methane evolved during the incubation period, respectively. Using this approach, the mass balance on carbon shows that 99.9% of the carbon can be accounted for with a standard deviation of 13.9 %. This can be seen on table 12.

From table 12, it can be seen that there was a difference between the carbon recovery of the different trials. The trials with the most gas production generally had the highest carbon recovery. The reason for this is unclear, however the total carbon recovery appears acceptable.

Table 12 Percent Carbon Recovery of Trials

			20° C w/straw Percent Carbon Recovery	30° Percent Carbon Recovery	20° Percent Carbon Recovery	10° Percent Carbon Recovery
Feedlot	closed	#1	95.9%	126.2%	113.9%	85.0%
Feedlot		#2	95.0%	127.1%	115.6%	90.0%
Feedlot	open	#1	79.7%	114.6%	87.5%	87.4%
Feedlot		#2	79.0%	110.4%	90.6%	90.8%
Pasture	closed	#1	95.7%	123.6%		
Pasture		#2	99.0%	130.4%		
Pasture	open	#1	81.7%	111.6%		
Pasture		#2	84.1%	113.0%		
Slurry	closed	#1	88.0%	105.2%	115.0%	86.9%
Slurry		#2	88.3%	107.8%	115.6%	92.0%
Slurry	open	#1	83.6%	99.5%	126.9%	89.5%
Slurry		#2	83.5%	96.7%	125.0%	91.9%
Slurry w/ inoculum	closed	#1		93.6%	122.0%	90.8%
Slurry w/ inoculum		#2		104.8%	116.9%	92.9%
Slurry w/ inoculum	open	#1		113.4%	96.8%	94.1%
Slurry w/ inoculum		#2		115.3%	92.7%	92.1%
Slurry with replenishment, open		#1			95.6%	91.6%
Slurry with replenishment, open		#2			98.9%	88.0%
Slurry and inoculum with replenishment	open	#1			92.1%	91.7%
Slurry and inoculum with replenishment	open	#2			95.4%	89.2%
Average			87.8%	112.1%	106.3%	90.3%
standard deviation			7.0%	10.9%	13.7%	2.4%
coefficient of variation			8.0%	9.7%	12.9%	2.7%

average carbon recovery of all trials	99.9%
standard deviation	13.9%
coefficient of variation	14.0%

Percent Carbon Recovery is the residual carbon after each trial plus the carbon evolved as methane or carbon dioxide gas, divided by the initial carbon. This was all on a mass basis.

With replenishment means aged water was added to sample weekly to maintain hydration. Aged water is water that has remained open to the atmosphere for a week, to dissipate chlorine.

With inoculum means a culture of methanogenic bacteria was added to the sample. Inoculum came originally from an anaerobic digestor at a waste treatment plant. This was then acclimated to dairy cattle manure by being fed dairy cattle manure periodically and exclusively over a period of several years.

In addition to calculations for carbon mass balance, calculations for non-volatile solids were done on all four trials. 94.2% of the non-volatile solids can be accounted, with a standard deviation of 11.9%. This calculation is the total beginning non-volatile solids (initial) minus the total ending non-volatile solids (final) divided by the total beginning non-volatile solids (initial). This calculation however does not take losses to the volatile solids portion, particularly the gasses into account. It also exhibits differences between trials, much as did the carbon balance calculation. More telling is the material balance described above, on total carbon.

These results are highly complimentary and indicate reasonable confidence in other results. A more approximate method may be used for the material balance. From McCarty, 1972, the "formula" for the solids portion of domestic wastewater is $C_{10}H_{19}O_3N$. Using this formula and the gram carbon per gram domestic wastewater as a surrogate for the fraction weight carbon in manure, a calculation for the amount of loss from these series of tests can also be made. Based on these assumptions, there is a recovery of 95.8% with a standard deviation of 9.9%. These results are consistent with the results presented earlier. This is in spite of the fact that the fermentable material was manure, not wastewater. Also the beginning material and material after fermentation could very likely have been different from each other, with differing percent carbons.

Methane Conversion Factors

Table 13 shows the final Methane Conversion Factors (MCF) for all trials and all waste treatment methods tested. Shown are the average and standard deviation of all results. Table 13 shows the assumed values from Casada and Safley (1990), listed here for comparative purposes, along with the comparable treatment results from this study. The designation of closed or open was added by the author to give a better indications of which results in the following tables with which to compare Casada and Safleys results. Closed means the incubator was kept closed for the entire weeklong collection period. Open means the incubator was open for six days of the collection period and then closed and the gas collected on the seventh day. Results were multiplied by seven to obtain weeklong gas production.

Table 14 lists the MCF found in this study alongside the assumed MCF listed by Casada and Safley (1990). The results of the MCF versus temperature were graphed using a cubic spline curve fit algorithm. By looking up the temperature a representative MCF could be determined from the graph. This then could be used to compare with the MCF assumed for different geographical areas in Casada and Safley's study. See Figure 11, 12 and 13 for graphs of MCF vs. temperature. It should be noted that Casada and Safley considered solid waste storage as functionally equivalent to drylot or pasture waste treatment methods. This author considered this treatment to be markedly different from those other two methods because solid storage tends to retain moisture better and allow better anaerobic conditions to develop. Thus the method with which solid storage was compared was the closed feedlot trial.

Table 13 Methane Conversion Factor (MCF) and Standard Deviations Determined for Various Waste Management Systems

	20° C Manure and Straw Trial		30° C Manure Trial		20° C Manure Trial		10° C Manure Trial	
	CH_4 Recovered/ Initial Bo		CH_4 Recovered/ Initial Bo		CH_4 Recovered/ Initial Bo		CH_4 Recovered/ Initial Bo	
Treatment	average MCF	Standard Deviation	average MCF	Standard Deviation	average MCF	Standard Deviation	average MCF	Standard Deviation
Feedlot(closed)	10.2%	0.3%	65.5%	3.0%	45.7%	1.0%	0.0%	0.0%
Feedlot(open)	1.3%	0.1%	2.0%	0.0%	0.3%	0.1%	0.0%	0.0%
Pasture (closed)	8.5%	0.5%	67.3%	6.7%				
Pasture(open)	1.0%	0.1%	2.0%	0.3%				
Slurry(closed)	5.2%	0.4%	75.6%	0.1%	55.3%	0.4%	0.2%	0.0%
Slurry(open)	1.6%	0.0%	5.4%	0.6%	50.9%	6.6%	0.2%	0.0%
Slurry and Inoculum(closed)			53.5%	9.2%	72.5%	1.9%	0.5%	0.0%
Slurry and Inoculum(open)			14.1%	1.7%	13.3%	2.6%	0.3%	0.0%
Slurry(open) with replenishment					21.1%	1.7%	0.0%	0.0%
Slurry and Inoculum(open) with replenishment					18.7%	0.1%	0.3%	0.3%

Table 14 U.S. Methane Emissions from Waste Management Systems

System type	MCF Casada and Safley's estimate	20° C Manure with Straw		30° C Manure		20° C Manure		10° C Manure		System Tested in Trials
		average MCF	Std. Dev.	average MCF	Std. Dev.	average MCF	Std. Dev.	average MCF	Std. Dev.	
Pasture/Range (open)	10.0%	1.0%	0.1%	2.0%	0.0%	0.3%	0.1%	0.0%	0.0%	Pasture/ feedlot (open)
Anaerobic Lagoon (closed)	90.0%									
Liquid/Slurry Storage (closed)	20.0%	5.1%	0.4%	75.6%	0.1%	55.3%	0.4%	0.2%	0.0%	Slurry (closed)
Drylot (open)	10.0%	1.3%	0.1%	2.0%	0.0%	0.3%	0.1%	0.0%	0.0%	Feedlot (open)
Solid Storage	10.0%	10.2%	0.3%	65.5%	3.0%	45.7%	1.0%	0.0%	0.0%	feedlot (closed)
Daily Spread (open)	5.0%									

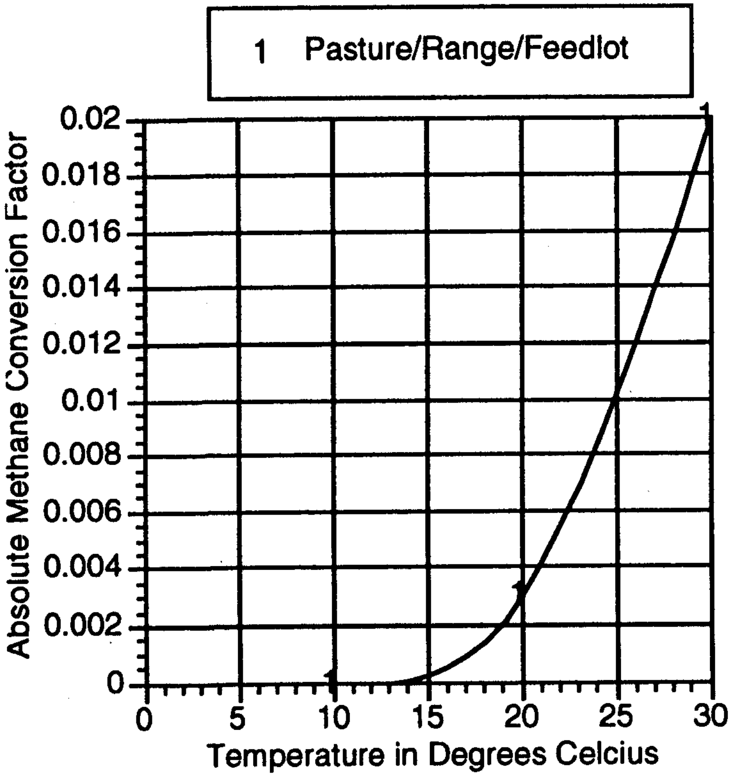


Figure 11
Methane Conversion Factor Versus Temperature for Range/Pasture/Feedlot Waste Management System

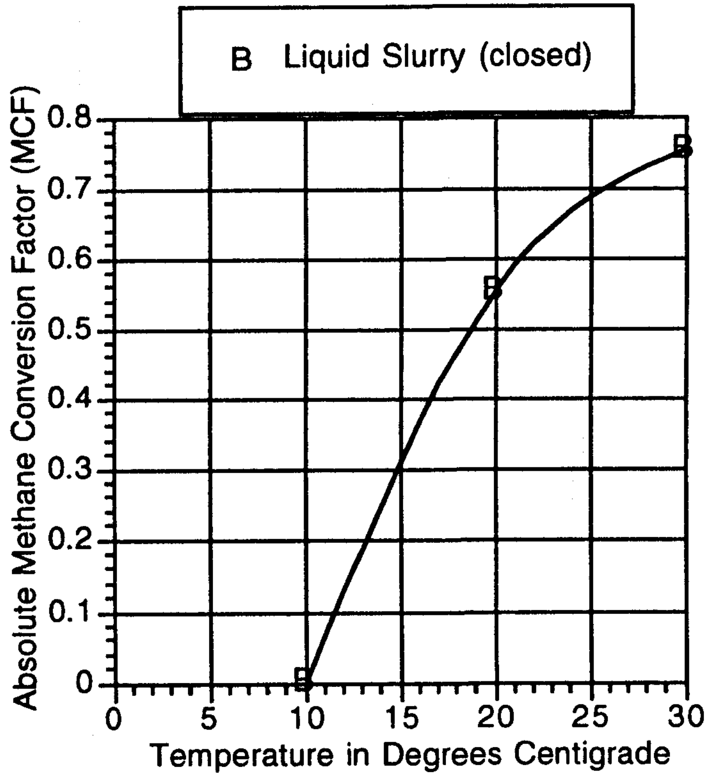


Figure 12
Methane Conversion Factor Versus Temperature for Slurry Waste Management System

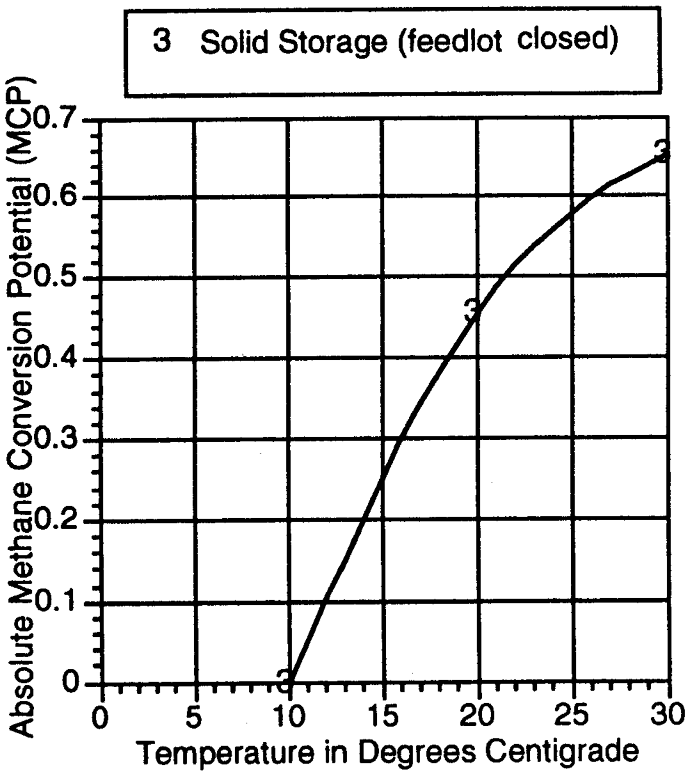


Figure 13
Methane Conversion Factor Versus Temperature for Solid Waste, Waste Management System

Biologic Methane Potential Conserved During Trials

Tables 15, 16, 17 and 18 list the methane recovered during the trial versus the difference between the starting and the ending Bo. In other words, it is an expression of the methane potential that is not lost during the trials. Table 19 gives an overall view of the retention of Bo potential across all the trials. Most obviously notable is the loss of Bo potential among the specimens that remained open to the atmosphere. Even though they were made anaerobic again in the process of determining the residual Bo, they still did not regain their original Bo potential. It should be noted that this is not an absolute measure of the retention of methane generating potential. It should also be noted that there was a problem in the 20° C manure trial. The temperature went out of control on two different occasions, undoubtedly contributing to the erroneous results indicating more than 100% MCF. This was unfortunate but must be considered when evaluating the results.

It should be emphasized that this last analysis is not an expression of the Methane Conversion Factor, but rather a measure of the amount of the Bo that is conserved by different waste treatment methods. Table 13 and 14, presented earlier present to Methane Conversion Factors (MCF) determined for the various waste management systems.

Table 15 Amount Of Methane Recovered (Observed During 20° C Manure With Straw Trial Plus Residual Methane) Compared to Total Methane Potential Showing Duplicate Results

	CH4 Recovered / Potential Change (observed / change)		
20° C Manure and Straw Trial	average	low replicate	high replicate
Feedlot(closed)	52.0%	46.9%	58.2%
Feedlot(open)	2.0%	1.9%	2.1%
Pasture (closed)	28.7%	23.1%	37.0%
Pasture(open)	1.5%	1.5%	1.6%
Slurry(closed)	31.8%	24.6%	42.8%
Slurry(open)	4.2%	4.1%	4.3%

Table 16 Amount Of Methane Recovered (Observed During 30° C Manure Trial Plus Residual Methane) Compared to Total Methane Potential Showing Duplicate Results

	CH4 Recovered / Potential Change (observed / change)		
30° C Trial	average	low replicate	high replicate
Feedlot(closed)	84.0%	81.6%	86.7%
Feedlot(open)	2.5%	2.4%	2.5%
Pasture (closed)	84.9%	78.6%	91.3%
Pasture(open)	2.5%	2.3%	2.7%
Slurry(closed)	96.8%	95.1%	98.7%
Slurry(open)	6.5%	6.1%	7.0%
Slurry and Inoculum(closed)*	69.2%	61.1%	82.2%
Slurry and Inoculum(open)*	17.9%	16.4%	19.3%

Table 17 Amount Of Methane Recovered (Observed During 20° C Manure Trial Plus Residual Methane) Compared To Total Methane Potential Showing Duplicate Results

20° C Trial	CH4 Recovered / Potential average	Change(observed / change) low replicate	high replicate
Feedlot(closed)	91.9%	91.3%	92.4%
Feedlot(open)	0.4%	0.3%	0.5%
Slurry(closed)	102.0%	94.7%	105.9%
Slurry(open)	86.7%	79.5%	92.1%
Slurry and Inoculum(closed)*	140.1%	140.2%	141.0%
Slurry and Inoculum(open)*	24.4%	20.8%	28.0%
Slurry(open) with replenishment	35.3%	34.5%	36.2%
Slurry and Inoculum(open) with replenishment	35.7%	33.9%	37.8%

Table 18 Amount of Methane Recovered (Observed During 10° C Manure Trial Plus Residual Methane) Compared To Total Methane Potential Showing Duplicate Results

10° C Trial	CH4 Recovered / Potential average	Change(observed / change) low replicate	high replicate
Feedlot(closed)	0.05%	0.04%	0.04%
Feedlot(open)	0.00%	0.00%	0.00%
Slurry(closed)	0.87%	0.81%	0.96%
Slurry(open)	0.56%	0.53%	0.57%
Slurry and Inoculum(closed)*	3.64%	3.04%	4.96%
Slurry and Inoculum(open)*	1.63%	1.47%	2.06%
Slurry(open) with replenishment	0.01%	0.00%	0.01%
Slurry and Inoculum(open) with replenishment	1.47%	0.44%	1.24%

Table 19 **Amount of Methane Recovered In All Trials (Observed plus Residual Methane) Compared To Total Methane Potential**

	CH4 recovered / potential Change (observed/change)			
	20° Manure and Straw Trial	30° C Manure Trial	20° C Manure Trial	10° C Manure Trial
Feedlot(closed)	52%	84.0%	91.9%	0.05%
Feedlot(open)	2%	2.5%	0.4%	0.00%
Pasture (closed)	29%	84.9%		
Pasture(open)	2%	2.5%		
Slurry(closed)	32%	96.8%	102.0%	0.87%
Slurry(open)	4%	6.5%	86.7%	0.56%
Slurry and Inoculum(closed)*		69.2%	140.1%	3.64%
Slurry and Inoculum(open)*		17.9%	24.4%	1.63%
Slurry(open) with replenishment			35.3%	0.01%
Slurry and Inoculum(open) with replenishment			35.7%	1.47%

Discussion

Relationship of Results to Earlier Estimates

Table 13 shows that the Casada and Safley's estimate for Pasture/Range and Drylot MCF to be much higher than the observed MCF under all tested temperature regimens. Casada and Safley's estimate for liquid/slurry storage is undoubtedly dependent on definition of the concentration of the slurry. According to Casada et al., 1992, a liquid/slurry system has a total solids concentration of something less than 12%, and an anaerobic lagoon has a concentration of about 2% total solids (Roos, 1992). The MCF value of 90% assumed for lagoons was based on Casada, Safley and Roos' extensive experience with lagoons. The total solids achieved in this study for liquid/slurry simulation was 11.05%, 8.93%, 8.84%, 8.73% for the 20° C manure with straw, 30° C manure, 20° C manure, and 10° C manure trial respectively. It is possible that as the sample becomes more hydrated, it achieves a higher MCF. This is what was observed. The higher results seen for the slurry specimen may be due to the samples being much less than the 12% total solids assumed for slurries. The same argument could be used for the solid storage (feedlot closed) results. In addition Casada and Safley (1990) consider solid storage to be equivalent to pasture treatement systems and this author considered them differently, as described earlier (Results, Methane Conversion Factor). Safley, et al., assert solid systems have a total solids content greater than about 20%. These studies never experienced a total solid content that high. They were 16.3%, 13.9%, 13.8%, and 13.6% total solids for the 20° C manure with straw, 30° C manure, 20° C manure, and 10° C manure trial respectively. It is notable that the most concentrated specimen, 16.3% total solids for the 20° C manure and straw specimen achieved near identical results with the Casada, et al, estimate for the solid storage regimen. The results for liquid/slurry and solid storage show the above referenced tendency for more dilute specimens to produce more methane. The samples that had much higher per cent total solids produced less methane.

Table 20 shows Casada and Safley's estimated methane production from manure broken down on a world wide basis. Table 21 shows the same results but adjusted based on the relative difference from the MCF observed and that assumed by Casada and Safley. Some very rough assumptions were made in Table 21. The average temperature for the various regions was assumed to the nearest 10 degrees. In addition, Casada and Safley (1992) used a Climate Adjustment Factor (CAF) to account for dry areas, and cold areas. The MCF was multiplied by the CAF to account for lower methane emissions under these less favorable conditions. The CAF for arid regions was 0.5 and for very cold areas was 0.8. A very cold area was defined as an area with an average January temperature of less than 0° C. No adjustment was made by Casada and Safley (1992) for the United States. Table 21 does not make any adjustments to account for Casada and Safley's CAF estimate. The total revised results were very similar to Casada and Safley's (1992) results even though individual categories were markedly different. The final revised results of 35.2 Tg/year were close to Casada and Safleys value of 28.3 Tg/year and close to Casada and Safley's expected range of 20 to 35 Tg/year.

Table 22 and 23 show a comparison between Casada and Safley (1992) and this study for methane produced from U.S. dairy waste. Using Casada and Safley's numbers for the percentage of animal waste management systems in use, the total animal mass, the volatile solids produced per animal mass per day, and ultimate Bo values for all fifty states, the total methane emissions for the United States from dairy manure was calculated. Casada and Safley calculated 1,013,428 mt/year. Using all of Casada and Safley's numbers and published assumptions, a total of 1,135,180 was calculated. The difference was most likely due to assumptions that Casada and Safley made as to the MCF for the "other" category. (The category of animal waste management system in use that was not anaerobic lagoon, liquid slurry, daily spread or solid storage). It was considered to be pasture by this author, and the MCF used was that assumed by Casada and Safley for pasture, 0.1. Some rounding differences probably also contributed to the difference. Average temperatures for all states in the United States were calculated by using all cities listed in Weather of U.S. Cities, Fourth Edition, 1992 (Bair, Frank, editor) and then taking an average to arrive at a state average. Using MCF taken from figures 11, 12, and 13 for the average temperature for each state, a MCF was read off for each state, for each waste treatment method. Daily spread was treated to be equivalent to pasture/range/feedlot treatment. Anaerobic lagoon was considered to produce no methane below 10° C, in keeping with the results found for other methods in this study. Giving the benefit to Casada and Safley's extensive experience with anaerobic lagoons, and their earlier stated MCF of 0.9, a value of 0.9

was assigned to the anaerobic lagoon MCF for values above 20°C. Values between 10 and 20° C was read off a linear plot between those numbers for the values of 0 and 0.9, respectively. The above mentioned "other" category was again assumed to be pasture and treated as such in this studies calculations. This study determined that there is 356,682 mt/year of methane being generated from dairy manure. This is substantially different than Casada and Safley's estimate by a factor of 0.35 . Undoubtedly the low average annual temperature for most of the states in the United States played a large part in reducing this number. An estimate based on monthly or quarterly averages would undoubtedly be higher as the higher summer temperatures promote methanogenesis. Casada and Safley (1992) state that zero percent of U.S. dairy cattle use pasture/range/paddock waste management systems (Casada and Safley, 1992, exhibit 17). This is an unusual statement but may be understandable on examining the request for data sheet sent to U.S. extension personnel. Under the category, Dairy, they ask for the percentage of animals under the following waste management systems. It is suspected that feedlot/pasture/range was under-reported.

Daily spread (solid/semi-solid)
Tie-stall/stanchion (solid, with storage)
Free stall (liquid/slurry storage)
Free stall (Anaerobic lagoon)
Other (please specify if over 5%)

Table 20
Global Waste Methane Emissions by Region and System (Tg/yr)
Source: Safley, et al., 1992

Waste Management System	North Am	West Eur	East Eur	Oceania	Latin Am	Afri	Near East and Med	Asia & Far East	Total
Pasture/Range	1.3	0.8	1.2	1.2	2.2	1.3	0.5	1.8	10.2
Liquid/Slurry	0.4	3.2	2.6	0.0	0.0	0.0	0.0	0.9	7.2
Solid Strorage	0.1	0.4	1.6	0.0	0.0	0.0	0.0	0.0	2.1
Anaerobic Lagoon	1.5	0.0	0.5	0.1	0.0	0.0	0.0	0.7	2.8
Drylot	0.3	0.0	0.1	0.0	0.1	0.1	0.0	0.9	1.5
Burned for Fuel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
Daily Spread	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.2	0.6
Other Systems	0.6	0.3	0.6	0.0	0.4	0.1	0.1	0.9	3.0
Total	4.2	4.9	6.5	1.3	2.9	1.5	0.7	6.4	28.3

Totals may not add due to rounding

Table 21
Revised Global Waste Methane Emissions by Region and System (Tg/yr)

Source of data: Safley, et al., 1992,
adjusted by percentage of MCF observed from that assumed by Safley, et al.

Waste Management System	North Am	West Eur	East Eur	Oceania	Latin Am	Afri	Near East and Med	Asia & Far East	Total
Assumed Average Temp	20° C	20° C	20° C	30° C	30° C	30° C	30° C	30° C	
Pasture/Range	0.0	0.0	0.0	0.2	0.4	0.3	0.1	0.4	1.5
Liquid/Slurry	1.0	8.0	6.5	0.0	0.0	0.0	0.0	2.7	18.2
Solid Strorage	0.5	1.8	7.2	0.0	0.0	0.0	0.0	0.0	9.5
Anaerobic Lagoon	1.5	0.0	0.5	0.1	0.0	0.0	0.0	0.7	2.8
Drylot	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2
Burned for Fuel	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Daily Spread	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Other Systems	0.6	0.3	0.6	0.0	0.4	0.1	0.1	0.9	3.0
Total	3.6	10.1	14.8	0.3	0.9	0.4	0.2	4.9	35.2

Totals may not add due to rounding

Table 22a Methane Emissions From U.S. Dairy Manure

State	State (abbreviation)	Average Temperature °C	Methane Conversion Factor Anaerobic Lagoon	Methane Conversion Factor Liquid Slurry	Methane Conversion Factor Daily Spread	Methane Conversion Factor Solid Storage	Methane Conversion Factor Pasture/Range /Feedlot
Alaska	AK	-0.5	0.00	0.00	0.00000	0.00	0.00000
Alabama	AL	11.9	0.15	0.12	0.00000	0.10	0.00000
Arkansas	AR	16.4	0.55	0.40	0.00050	0.32	0.00050
Arizona	AZ	17.0	0.60	0.41	0.00075	0.34	0.00075
California	CA	15.8	0.50	0.36	0.00050	0.30	0.00050
Colorado	CO	9.5	0.00	0.00	0.00000	0.00	0.00000
Connecticut	CT	10.5	0.00	0.03	0.00000	0.02	0.00000
Delaware	DE	12.2	0.15	0.14	0.00000	0.10	0.00000
Florida	FL	21.9	0.90	0.61	0.00550	0.51	0.00550
Georgia	GA	17.5	0.65	0.44	0.00100	0.37	0.00100
Hawaii	HI	24.1	0.90	0.66	0.00800	0.56	0.00800
Iowa	IA	8.7	0.00	0.00	0.00000	0.00	0.00000
Idaho	ID	10.0	0.00	0.00	0.00000	0.00	0.00000
Illinois	IL	9.9	0.00	0.00	0.00000	0.00	0.00000
Indiana	IN	11.0	0.10	0.06	0.00000	0.04	0.00000
Kansas	KS	12.2	0.20	0.14	0.00000	0.10	0.00000
Kentucky	KY	12.9	0.25	0.18	0.00000	0.14	0.00000
Louisianna	LA	19.6	0.90	0.53	0.00275	0.44	0.00275
Massachusetts	MA	8.7	0.00	0.00	0.00000	0.00	0.00000
Maryland	MD	12.8	0.23	0.18	0.00000	0.14	0.00000
Maine	ME	8.7	0.00	0.00	0.00000	0.00	0.00000
Michigan	MI	7.0	0.00	0.00	0.00000	0.00	0.00000
Minnesota	MN	4.9	0.00	0.00	0.00000	0.00	0.00000
Missouri	MO	12.7	0.23	0.18	0.00000	0.14	0.00000
Mississippi	MS	17.5	0.65	0.44	0.00100	0.37	0.00100
Montana	MT	6.6	0.00	0.00	0.00000	0.00	0.00000
North Carolina	NC	15.3	0.40	0.33	0.00025	0.27	0.00025
North Dakota	ND	4.9	0.00	0.00	0.00000	0.00	0.00000

Table 22b Methane Emissions From U.S. Dairy Manure

State	State (abbreviation)	Average Temperature °C	Methane Conversion Factor Anaerobic Lagoon	Methane Conversion Factor Liquid Slurry	Methane Conversion Factor Daily Spread	Methane Conversion Factor Solid Storage	Methane Conversion Factor Pasture/Range /Feedlot
Nebraska	NE	9.7	0.00	0.00	0.00000	0.00	0.00000
New Hampshire	NH	2.2	0.00	0.00	0.00000	0.00	0.00000
New Jersey	NJ	12.0	0.20	0.14	0.00000	0.10	0.00000
New Mexico	NM	13.7	0.30	0.21	0.00000	0.18	0.00000
Nevada	NV	12.2	0.20	0.14	0.00000	0.10	0.00000
New York	NY	9.9	0.00	0.00	0.00000	0.00	0.00000
Ohio	OH	10.2	0.00	0.00	0.00000	0.00	0.00000
Oklahoma	OK	15.6	0.40	0.33	0.00025	0.27	0.00025
Oregon	OR	11.3	0.10	0.08	0.00000	0.08	0.00000
Pennsylvania	PA	10.4	0.00	0.03	0.00000	0.02	0.00000
Rhode Island	RI	10.1	0.00	0.00	0.00000	0.00	0.00000
South Carolina	SC	17.1	0.60	0.41	0.00075	0.34	0.00075
South Dakota	SD	7.2	0.00	0.00	0.00000	0.00	0.00000
Tennessee	TN	14.9	0.40	0.31	0.00025	0.24	0.00025
Texas	TX	18.9	0.80	0.50	0.00125	0.44	0.00125
Utah	UT	10.9	0.10	0.08	0.00000	0.08	0.00000
Virginia	VA	14.1	0.35	0.24	0.00000	0.20	0.00000
Vermont	VT	6.7	0.00	0.00	0.00000	0.00	0.00000
Washington	WA	9.9	0.00	0.00	0.00000	0.00	0.00000
Wisconsin	WI	7.4	0.00	0.00	0.00000	0.00	0.00000
West Virginia	WV	11.4	0.10	0.08	0.00000	0.08	0.00000
Wyoming	WY	7.2	0.00	0.00	0.00000	0.00	0.00000

Waste per day (kg volatile Solids/day/1000 kg animal mass) = 10 Casada and Safley (1992), exhibit 8
Methane Conversion Factor dairy (m^3/kg volatile solids) = 0.24 Casada and Safley (1992), exhibit 4

Table 22c Methane Emissions From U.S. Dairy Manure

State	Total Animal Mass (mt)	Anaerobic Lagoon	Liquid Slurry	Daily Spread	Solid Storage	Other	Weighted Average MCF (f of Bo)	Weighted Average MCF listed in Casada and Safley (1992) (f of Bo)	CH4 Emissions Calculated from Derived MCF (mt/year)	CH4 Emissions Calculated from Casada and Safley's Assumed MCF (mt/year)
AK	1,578	10%	71%	2%	2%	15%	0.00	0.35	0	346
AL	33,184	50%	0%	50%	0%	0%	0.08	0.48	1,557	9,967
AR	58,140	25%	0%	75%	0%	0%	0.14	0.26	5,016	9,459
AZ	72,080	10%	0%	0%	0%	90%	0.06	0.18	2,737	8,118
CA	927,860	40%	0%	0%	0%	60%	0.20	0.48	116,289	278,676
CO	65,280	5%	10%	85%	0%	0%	0.00	0.11	0	4,493
CT	30,464	0%	53%	47%	1%	0%	0.02	0.13	307	2,478
DE	7,072	5%	35%	60%	0%	0%	0.06	0.15	250	664
FL	142,800	2%	0%	10%	0%	88%	0.02	0.11	2,090	9,829
GA	89,760	35%	5%	5%	0%	55%	0.25	0.43	14,047	24,151
HI	10,064	31%	57%	6%	0%	6%	0.66	0.40	4,132	2,519
IA	267,920	3%	20%	8%	65%	4%	0.00	0.14	0	23,470
ID	147,492	10%	85%	2%	0%	3%	0.00	0.26	0	23,995
IL	174,080	5%	15%	45%	10%	25%	0.00	0.13	0	14,160
IN	160,480	10%	60%	20%	10%	0%	0.05	0.23	5,021	23,095
KS	90,236	0%	40%	60%	0%	0%	0.06	0.11	3,162	6,211
KY	184,280	19%	8%	30%	0%	43%	0.06	0.25	7,137	28,827
LA	71,740	6%	0%	4%	0%	90%	0.06	0.16	2,540	7,182
MA	24,684	0%	29%	58%	13%	0%	0.00	0.10	0	1,545
MD	94,588	2%	48%	45%	5%	0%	0.10	0.14	5,794	8,286
ME	38,284	0%	29%	58%	13%	0%	0.00	0.10	0	2,395
MI	309,332	5%	30%	45%	12%	8%	0.00	0.15	0	29,033
MN	726,920	0%	30%	40%	30%	0%	0.00	0.11	0	50,033
MO	196,520	60%	0%	40%	0%	0%	0.14	0.56	16,969	68,861
MS	58,616	10%	1%	2%	2%	85%	0.08	0.19	2,849	6,969
MT	20,332	12%	19%	39%	23%	7%	0.00	0.20	0	2,544
NC	90,372	5%	35%	50%	10%	0%	0.16	0.15	9,196	8,482
ND	69,836	0%	20%	10%	70%	0%	0.00	0.12	0	5,244

Table 22d Methane Emissions From U.S. Dairy Manure

State	Total Animal Mass (mt)	Anaerobic Lagoon	Liquid Slurry	Daily Spread	Solid Storage	Other	Weighted Average MCF (f of Bo)	Weighted Average MCF listed in Casada and Safley (1992) (f of Bo)	CH4 Emissions Calculated from Derived MCF (mt/year)	CH4 Emissions Calculated from Casada and Safley's Assumed MCF (mt/year)
NE	84,320	0%	5%	35%	0%	60%	0.00	0.10	0	5,276
NH	19,040	0%	40%	20%	40%	0%	0.00	0.13	0	1,549
NJ	26,112	0%	29%	58%	13%	0%	0.05	0.10	876	1,634
NM	50,456	90%	0%	10%	0%	0%	0.27	0.82	8,524	25,888
NV	16,252	1%	1%	8%	90%	0%	0.09	0.11	950	1,119
NY	692,376	0%	20%	70%	10%	0%	0.00	0.09	0	38,991
OH	333,336	5%	30%	45%	12%	8%	0.00	0.15	0	31,286
OK	89,420	15%	0%	5%	0%	80%	0.06	0.46	3,369	25,738
OR	84,864	42%	35%	5%	1%	17%	0.07	0.49	3,760	26,019
PA	626,960	0%	2%	95%	3%	0%	0.00	0.06	471	23,538
RI	2,156	0%	29%	58%	13%	0%	0.00	0.10	0	135
SC	35,020	80%	5%	10%	5%	0%	0.52	0.74	11,341	16,215
SD	116,008	25%	25%	30%	20%	0%	0.00	0.31	0	22,502
TN	175,440	5%	40%	20%	0%	35%	0.14	0.21	15,823	23,053
TX	298,520	25%	60%	15%	0%	0%	0.50	0.35	93,429	65,376
UT	68,884	1%	1%	8%	90%	0%	0.07	0.11	3,181	4,741
VA	134,640	0%	75%	25%	0%	0%	0.18	0.16	15,164	13,479
VT	140,828	0%	29%	58%	13%	0%	0.00	0.10	0	8,812
WA	196,384	40%	50%	10%	0%	0%	0.00	0.47	0	57,754
WI	1,561,620	0%	15%	70%	15%	0%	0.00	0.08	0	78,170
WV	22,440	2%	40%	30%	20%	8%	0.05	0.14	702	1,966
WY	7,276	12%	19%	39%	23%	7%	0.00	0.20	0	911
								sum	356,682	1,135,180

Values of MCF for Anaerobic Lagoon taken from temp <10.3 MCF = 0
10.3<temp<20 MCF=.09*(temp-10)
temp > 20 MCF = 0.9

Values of MCF other than for Anaerobic Lagoon taken from figure 11,12and 13

Animal waste management system in use for each state taken from Casada and Safley (1992), Table H2

Environmental Implications

Casada and Safley assume a Methane Conversion Factor (MCF) for estimating the amount of methane that is evolved into the atmosphere by various waste treatment systems. The assumed values were generally higher than the values obtained in this study. The most common waste treatment system, pasture/range deposition, which accounts for 35% of the waste stream, (exhibit 32, Safley et al., 1992) achieved less than one fifth of the MCF assumed by Casada and Safley. In view of these findings, the MCF of waste treatment regimens that were not investigated in this study but were estimated by Casada and Safley, need to be reevaluated.

The liquid slurry regimen and the solid storage regimens did achieve higher MCF's than the Casada and Safley estimates at all but the lowest temperature trial (10° C). These together treat 33% of the waste stream. It must be noted however that the amount of methane produced during the 10°C trial was negligible. Corvallis, Oregon with a mean average annual temperature of 11° C would fall into this category, as would a large section of the United States, Canada, Europe and Asia. See Figure 14 for a graph of the mean monthly temperature for Corvallis, Oregon. If the amount of methane was estimated from annual data alone, then the amount from a climate such as Corvallis would be negligible.

An examination of figure 15, for the plot of Ontario, Oregon reveals a region with the same annual mean temperature as Corvallis, Oregon, but with much higher and lower monthly mean temperatures. Corvallis did not have one monthly average temperature above 18.7° C, whereas Ontario, Oregon had three months of average mean monthly temperatures above 20° C. Because negligible amounts of methane are produced at around 10° C or below, one important factor in methane production is the amount of time the temperature is above this range. Ontario, with its extremes in climate would therefore be expected to produce more methane for all waste treatment systems.

Similarly, Figure 16 and 17 show the temperature graphs of Orlando, Florida and Phoenix, Arizona. Both have similar Mean Annual Temperatures, of about 22° C, but Phoenix, Arizona has much higher and lower extremes in temperature. The amount of methane produced in each region would depend more on the relative mix of treatment methods because, unlike the Oregon examples, the monthly means were generally much higher than 10° C. It is only at the low temperature range that relatively little methane is produced, regardless of treatment method.

A better estimate of the amount of methane evolved globally from manures would take into account not only average annual temperatures but monthly or quarterly averages. Such a model would use monthly or quarterly temperatures and relative regional mixes of waste management systems to estimate global methane emissions.

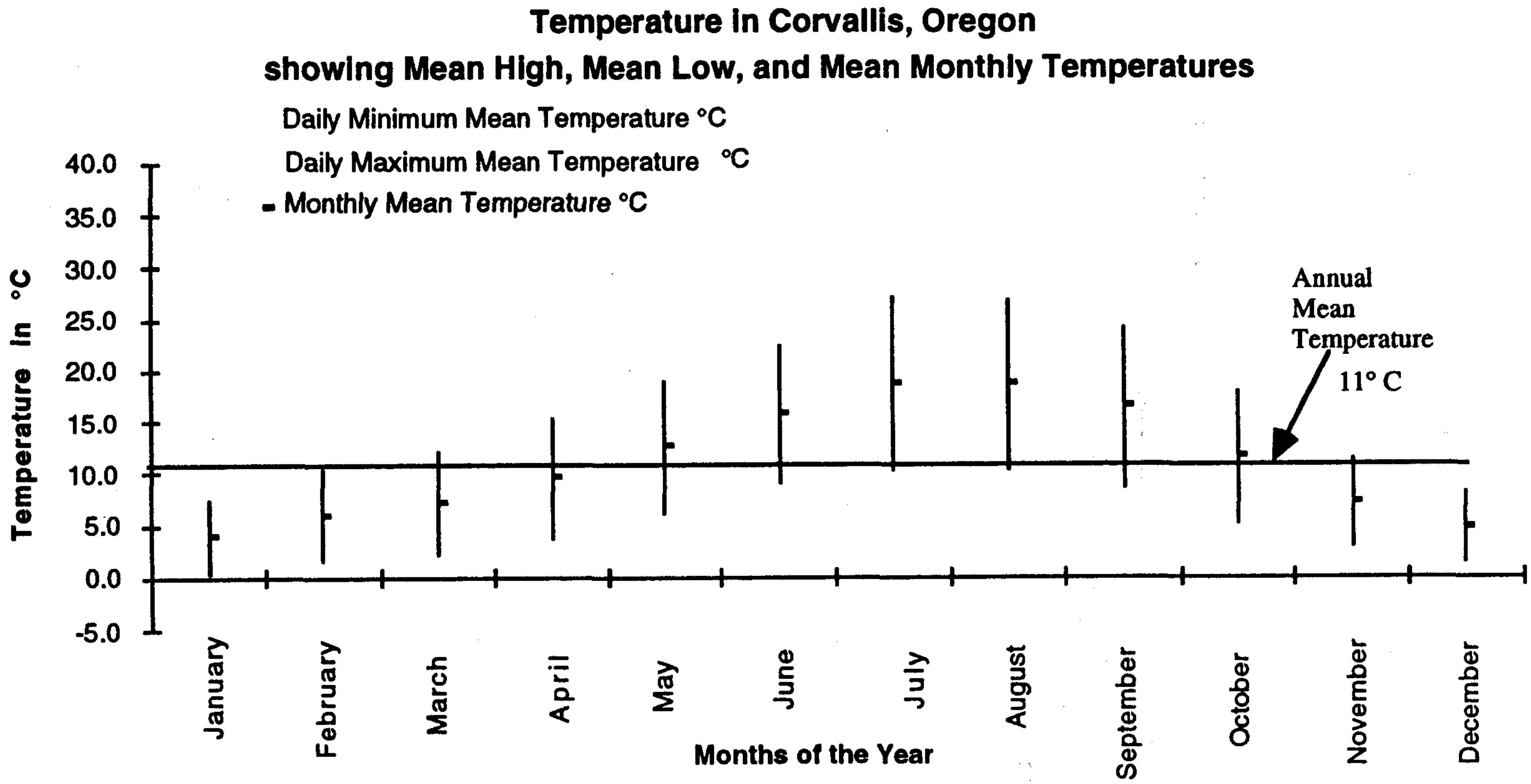


Figure 14 Annual Average Temperature Ranges for Corvallis, Oregon
Source of Data: Blanchard, et al., 1985

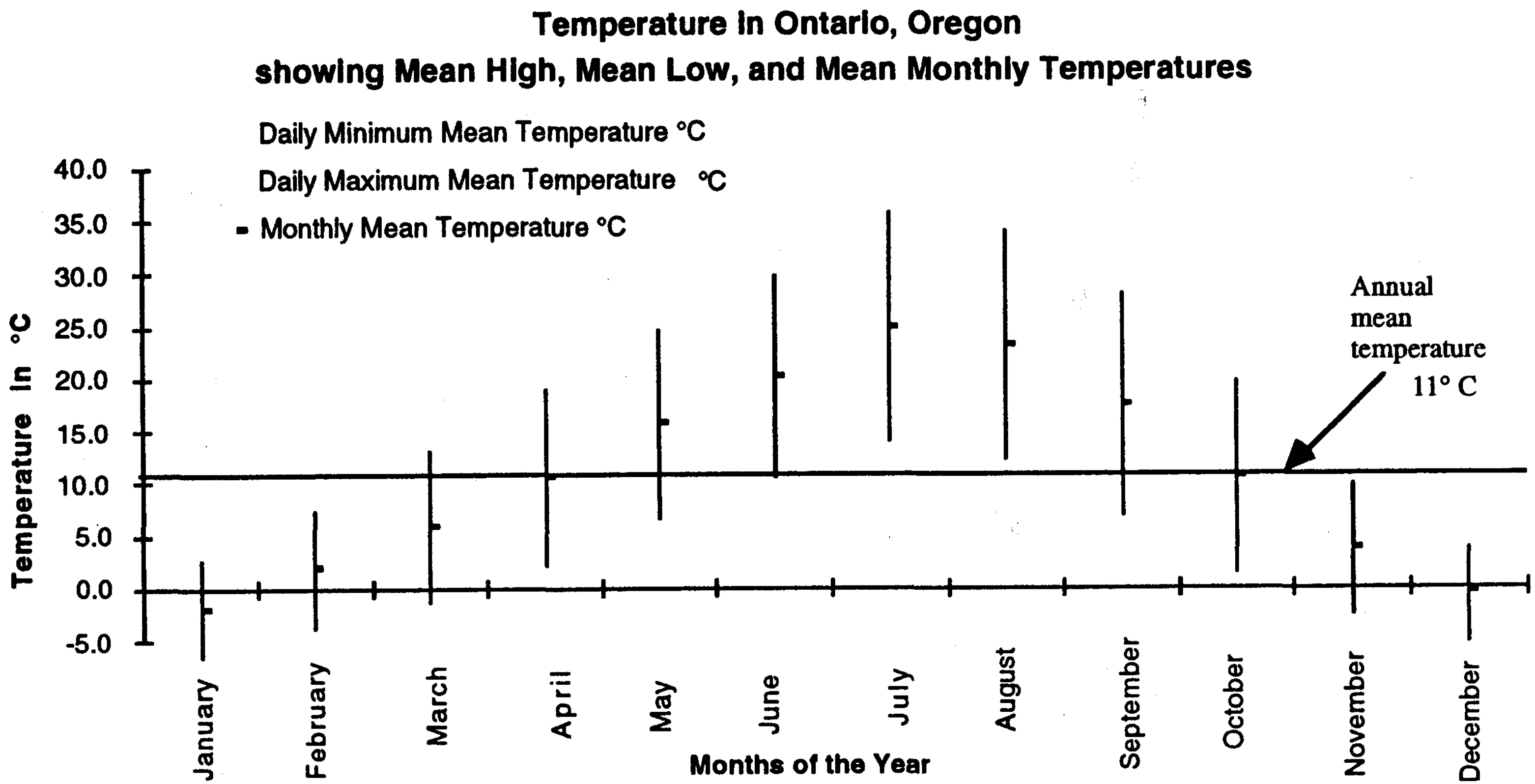


Figure 15 Annual Average Temperature Ranges for Ontario, Oregon
Source of Data: Blanchard, et al., 1985

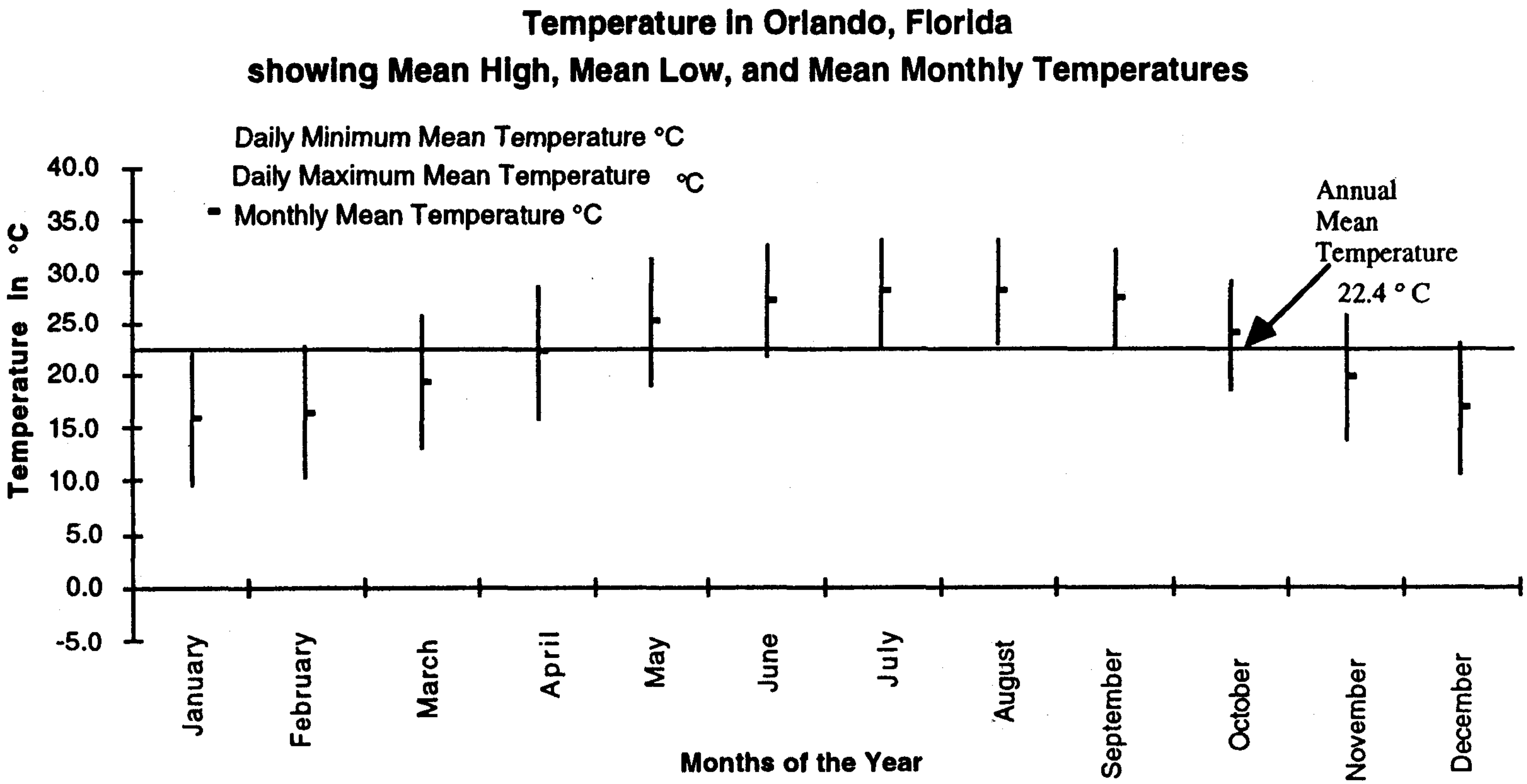


Figure 16 Annual Average Temperature Ranges for Orlando, Florida
Source of Data: Blanchard, et al., 1985

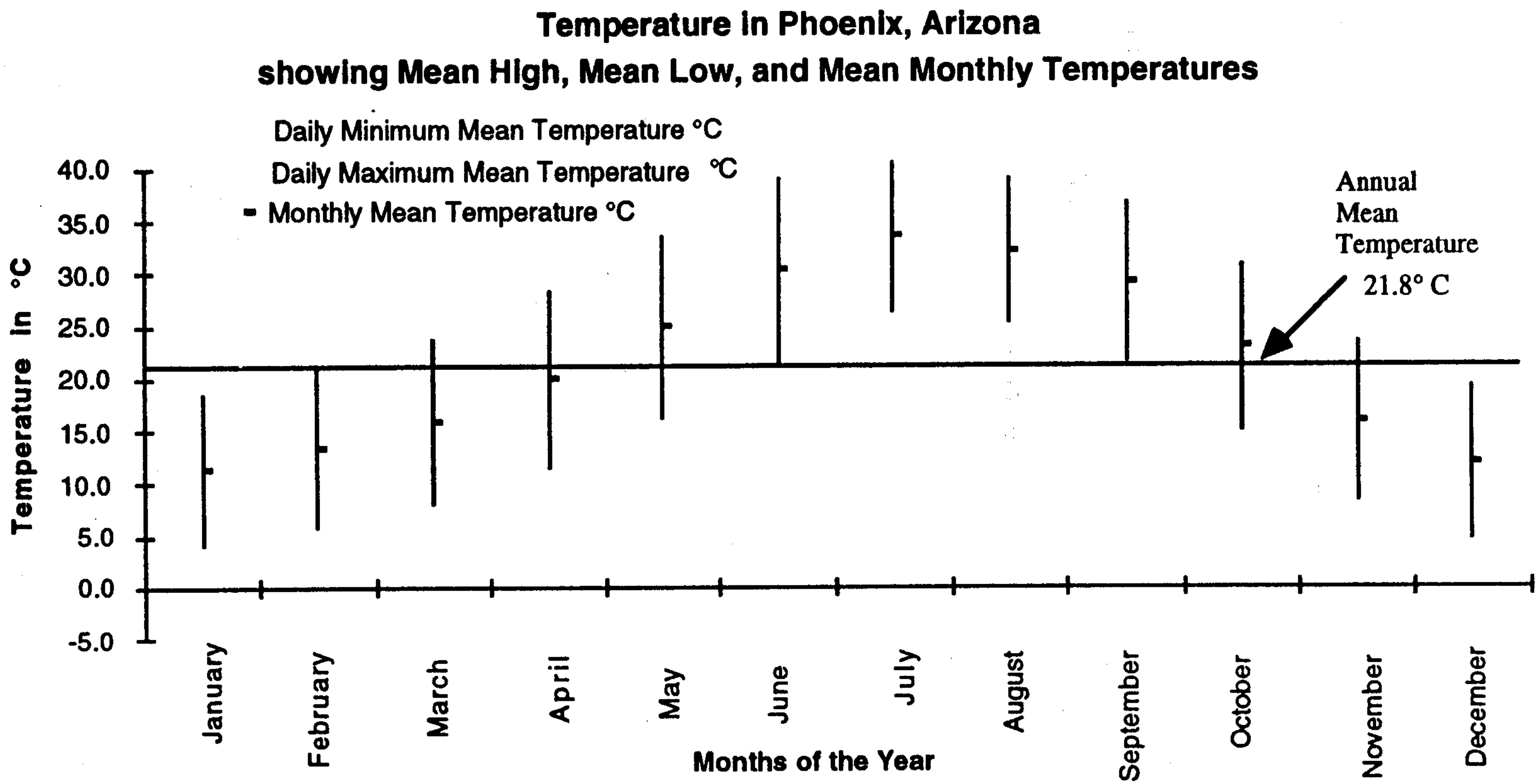


Figure 17 Annual Average Temperature Ranges for Phoenix, Arizona
Source of Data: Blanchard, et al., 1985

Carbon Cycling

Carbon cycling is an important consideration when evaluating sources of greenhouse gas. Drennen and Chapman (1992) point out that methane released from ruminant animals is not the same as methane released from natural gas pipelines or from coal mining operations. The former simply recycle carbon that is already in the atmosphere while the latter puts back into the atmosphere that which was removed tens of thousands of years ago. Table 23 presented by Drennen and Chapman (1992) show steady state carbon and greenhouse gas cycles in a 500 kg beef animal fed 9 kg per day (dry weight) of silage (40% carbon content). This amounts to 3600 g of carbon, of which the cow immediately returns 2095 g of carbon to the atmosphere as CO_2. Manure accounts for 1238 g of carbon, which is deposited as manure. Drennen and Chapman assume "proper waste handling" so that no methane is produced (presumably daily spread), thus the manure degrades to carbon dioxide exclusively. Of the remaining quantities, 173 g of carbon in the form of CO_2 and 94 g of carbon in the form of CH_4 are released by belching. Using a greenhouse warming potential of 10 for CH_4, in recognition of atmospheric lifetimes yields a total greenhouse warming increase of 6.9% comparing input to output gasses. Similar logic applies to every other source of biologically derived methane.

Table 23 Steady State Daily Carbon and Greenhouse Gas Cycles in a 500 kg Beef Animal

All figures are in g/day

	Carbon	CO2	CH4	Greenhouse Warming Equivalent Units
Inputs:				
Approximately 9 kg/day silage (dry wt.)	3600	13200		13200
Outputs:				
Carbon in CO2--belching	173	634		
Carbon in CH4--belching	94		125	1250
Carbon in manure (1238 g)				
Carbon released as CO2	1238	4539		4539
Carbon released as CH4	0			
Carbon into soil	0			
Carbon in CO2--respiration	2095	7682		7682
Carbon in urine	0			
Totals	3600	12855	125	14105

Source: Drennen and Chapman, 1992
Where the greenhouse warming equivalent unit is the greenhouse warming equivalent effect as one gram of CO_2. CH_4 has 10 times the greenhouse warming effect as CO_2 on a gram basis as per Lashof and Ahuja, 1990.

Considering both the atmospheric residence time and carbon cycling yield a better perspective on ruminants contribution to greenhouse warming. Using Drennen and Chapman's calculations, assuming a cow emits 58 kg of methane per year. This is equivalent to 3625 mole of methane (58 kg/ 16 g/mole * 1000). Using Lashof's Global Warming Potential index of 3.7 (mole basis, 16/44 * 10), the emissions per cow have the same impact as 13,413 mole of CO_2 (3.7 * 3625). One kg of coal produces 7.56 MJ (2.1 kWh) of electricity and 41.66 mole of CO_2. (assumes low rank bituminous coal, 50%

carbon, 13,000 B.t.u. per lb and approximately 30% efficiency in energy conversion). Therefore 13,413 mole of CO_2 is the end product of producing 2431 MJ (676 kWh) of electricity ((13413/41.66)*7.56). This is approximately the amount of electricity consumed by one 75 watt light bulb in a year (75*24*365).

If the carbon cycling is considered this result is even lower. The cow emits 58 kg of methane per year. This methane is from recycled carbon dioxide, carbon dioxide that has been removed from the atmosphere. Thus the emission per cow of methane that has the equivalent value of 13, 413 mole of CO_2 counterbalanced by 3625 moles of CO_2 that were removed from the atmosphere. Therefore the increase in methane is equivalent to the impact of 9,788 mole of CO_2 (13,413-3,625). Therefore 9,788 mole of CO_2 is the end product of producing 1776 MJ (493 kWh) of electricity from coal ((9788/41.66)*7.56). This is approximately the amount of electricity consumed by one 56 watt light bulb in a year (56*24*365).

Conclusion

Methane is a potent greenhouse gas as seen be its relative greenhouse effect compared to carbon dioxide. As seen on Table 2, methane has 58 times the greenhouse warming effect on a mass basis for equal masses of gas released into the atmosphere. Figure 7 and 8 show the relative effect of a number of greenhouse gasses on green house warming used on a per mass comparison to carbon dioxide (Ramanathan et al., 1985 and Hansen et al., 1988). These two studies neglect the atmospheric residence times of the two gasses. Lashof and Ahuja (1990) proposed an alternative weighting index that takes atmospheric residence time into account. Using an arguable atmospheric lifetime of 100 years for carbon dioxide and 10 years for methane, Lashof and Ahuja developed the relationships shown in figure 9. They show that carbon dioxide (including carbon dioxide originating as carbon monoxide) contributes 78.2% of the global warming potential of current greenhouse gas emissions. Methane only contributes 9.2% of the global warming potential. Using Casada and Safley's estimate of methane produced from manures, methane contributes 5% of the total methane budget as seen in figure 6. In other words, manures are responsible for 5% of 9.2% (or 0.46%) of the greenhouse effect. Theoretical and numerical analyses agree that the increase of greenhouse gasses (due primarily to the burning of fossil fuels) in the atmosphere will cause a warming of the global average temperature of 1.4° to 4.5° C during the 21st century (Taylor and MacCracken, 1990). Thus if manure fermentation is responsible for 0.46% of this effect, then manure fermentation is responsible for between 0.006 and 0.021° C rise in global average temperature. This amount is small enough to be considered inconsequential.

In conclusion, it can be seen that when carbon cycling and atmospheric life span are considered, methane production from manure produces a negligible effect to greenhouse warming. In addition methane production from ruminants produce little effective greenhouse warming when considered in relation to other sources of greenhouse gas, primarily fossil fuels.

This study substantiated earlier estimates of global methane production done by Casada and Safley (1992). However some sources of methane produced more than earlier estimates and some produced less. In whole however, the Casada and Safley's total world wide estimates were consistent with the findings in this report. The amount of methane produced by U.S. dairy waste as determined in this report was substantially lower than estimates made by Casada and Safley (1992). This was due to the low average annual temperature in most of the United States and the relative lack of methanogenic activity below 10° C. Had similar care been used to determine average temperatures on a world wide basis, the earlier findings in this report with regard to world wide methane emissions would undoubtedly been much lower.

Bibliography

Bair, Frank, editor, Weather of U.S. Cities, Fourth Edition, 1992, Gale Research, Inc, Detroit, MI

Blanchard, Carol, Arthur Chartow, Fredrick G. Ruffner, James M. Ethridge, Dedria Bryfonski, Ellen T. Crowley, Climates of the United States, National Oceanic and Atmospheric Administration, Gale Research Company, Detroit Michigan, 1985

Casada, M.E., L.M. Safley, Jr., Global Methane Emissions From Livestock and Poultry Manure, Biological and Agricultural Engineering Department, North Carolina State University, June 6, 1990

Chen, T.H., D.L. Day, and M.P. Steinberg, Methane Production from Fresh Versus Dry Dairy Manure, Biological Wastes, 1988, vol 24 pp 297-306

Cleucer, Lenore, Arnold E. Greenburg, R. Rhodes Trussell, eds., Standard Methods for the Examination of Water and Wastewater, 17th Edition, American Public Health Association, American Water Works Association, Water Pollution Control Federation, 1989

Crutzen, P.J., I. Aselmann and W. Seiler, Methane Production By Domestic Animals, Wild Ruminants, and other Herbivorous Fauna, and Humans, Tellus vol 38B, pp. 271-284, #3-4 July-Sept 1986

Downing, Ralph C., Fluorocarbon Refrigerants Handbook, Prentice Hall, New Jersey, 1988

Drennen, Thomas E. and Duane Chapman, Negotiating a Response to Climate Change: Role of Biological Emissions, Contemporary Policy Issues, Vol 10, July 1992, pp. 49-58

Edgar Tom, Feasibility Study for a Tillamook County Dairy Waste Treatment and Methane Generation Facility, Oregon State University, Master Thesis, 1992

Fischer, Steven K., Phillip D. Fairchild, Patrick J. Hughes, Global Warming Implications of Replacing CFC's, ASHRAE Journal, v. 34, pp. 14-19, April 1992

Ganic, Ejup N., Tyler G. Hicks, editors, The McGraw-Hill Handbook of Essential Engineering Information and Data, McGraw-Hill, inc., New York, 1991

Gaudy, Anthony F., Jr., Elizabeth T. Gaudy, Elements of Bioenvironmental Engineering, Engineering Press, Inc., San Jose, California, 1988

Hansen, J., I. Fung, A. Lacis, S. Lebedeff, D. Rind, R. Ruedy, G. Russell, and P. Stone, Global Climate Change as Forecadst by the GISS 3-D Model Journal of Geophysical Research, 1988, Vol 93, pp 9341-9364

Hashimoto, Andrew G., Effect of Mixing Duration and Vacuum on Methane Production Rate from Beef Cattle Waste, Biotechnology and Bioengineering, Vol. XXIV, John Wiley & Sons, Inc., 1982, pp. 9-23

Hashimoto, Andrew, Effect of Inoculum/ Substrate Ratio on Methane Yield and Production Rate from Straw, Biological Wastes Vol 28, 1989, pp 247-255

Houghton J. T., G.J. Jenkins, J.J. Ephraums, editors, IPCC-Intergovernmental Panel on Climate Change, 1990: Climate Change: The IPCC Scientific Assessment, Cambridge University Press, 1990

Houghton, J.T., G.J. Jenkins, and J.N. Ephraums, eds., Climate Change: The IPCC Scientific Assessment, Intergovernmental Panel on Climate Change, New York: Cambridge University Press 1990.

Lashof, D and D. Ahuma, "Relative Contributions of Greenhouse Gas Emissions to Global warming," Nature, Vol 343, April 5, 1990, pp 529-531

Lashof, Daniel A., and Dennis A. Tirpak, Policy Options For Stabilizing Global Climate, Hemisphere Publishing Corporation, New York, 1990

McCarty, Perry L., Energetics and Bacterial Growth, Stanford University, Marcel Dekker, Inc., 1971, pp 495-531

McCarty, Perry L., Stoichiometry of Biological Reactions, Presented at the International Conference, "Toward a Unified Concept of Biological Waste Treatment Design," Atlanta, Georgia, October 6, 1972

McEvedy, J., and R. Jones, Atlas of World Population History, Middlesex, United Kingdom, Penquin, 1978

Nelson, Thomas P., and Sharon L. Wevill, "Alternative Formulations and Aerosol Dispensing Systems" in Alternative Formulations and Packaging to reduce use of Chlorofluorocarbons (CFC), Noyes Data Corporation, Park Ridge, New Jersey, 1990

Patterson, A.J., "Potential Methane Emissions from Animal Manure," in Proceedings of Workshop on Greenhouse Emissions from Agricultural Systems, IPCC-RSWG, Subgroup on Agriculture, Forestry, and other Human Activities, Vol. 1, Office of Policy Analysis, USEPA, Washington, D.C., December 1989, V59-V65

Ramanathan, V., R.J. Cicerone, H.B. Singh, and J.T. Kiehl, Trace Gas Trends and Their Potential Role in Climate Change, Journal of Geophysical Research, Vol 90, pt 6, pp. 5547-5566

Ron Moreau, The Saigon Virus: It's Catching, Newsweek, April 12, 1993, pg 34

Roos, Kurt F., 1992, personal communications

Safley, Jr, L.M., M.E. Casada, Jonathan Woodbury, Kurt F. Roos, Global Methane Emissions From Livestock and Poultry Manure, USEPA, Washington, D.C., February 1992, EPA/400/1-91/048

Salas, Carl E. and Marianne Salas, Guide to Refrigeration CFC's, The Fairmont Press, Inc., Lilburn, Georgia, 1992

Taylor, Karl E., and Michael C. MacCracken, Projected Effects of Increasing Concentrations of Carbon Dioxide and Trace Gases on Climate, Impact of Carbon Dioxide, Trace Gases and Climate Change on Global Agriculture, Bruce A. Kimball, editor, American Society of Agronomy, Inc., 1990

Yancun, C., H. Cong and Liang Pusen, Development of a new energy village-Xinbu, China, In Integrated Rural Energy Plannings edited by Y. El Mahgary and A.K. Biswas, Butterworths Publishing, Guildsford, England pp. 99-108

APPENDIX

20º Manure and Straw trial

Beginning Conditions

			Beginning Total Weight (g)	Beginning % Dry Wt.	Beginning % Vol. Sol.	Beginning Total Volatile Solids (g)	Beginning Non-Volatile Solids (g)	Ending Total Weight (g)	Ending % dry weight
Feedlot	closed	# 1	5100	16.31%	86.77%	721.8	110.1	4946	14.51%
Feedlot		# 2	5100	16.31%	86.77%	721.8	110.1	4957	14.36%
Feedlot	open	# 1	5100	16.31%	86.77%	721.8	110.1	2674	20.88%
Feedlot		# 2	5100	16.31%	86.77%	721.8	110.1	2691	20.59%
Pasture	closed	# 1	5100	16.31%	86.77%	721.8	110.1	4922	14.78%
Pasture		# 2	5100	16.31%	86.77%	721.8	110.1	4943	15.08%
Pasture	open	# 1	5100	16.31%	86.77%	721.8	110.1	2815	20.41%
Pasture		# 2	5100	16.31%	86.77%	721.8	110.1	2795	21.03%
Slurry	closed	# 1	7790	11.05%	87.22%	751.0	110.0	7610	9.41%
Slurry		# 2	7790	11.05%	87.22%	751.0	110.0	7615	9.65%
Slurry	open	# 1	7790	11.05%	87.22%	751.0	110.0	4548	14.23%
Slurry		# 2	7790	11.05%	87.22%	751.0	110.0	4702	13.74%

20º Manure and Straw trial

Ending Conditions

			Ending % volatile solids	Ending Total Volatile Solids (g)	Ending Non-Volatile Solids (g)	Change in non-volatile solids (initial-final)/initial)	CH4 Prod. mls/gvs	CO2 Prod. mls/gvs	Liters of CH4	Liters of CO2
Feedlot	closed	# 1	84.66%	607.5	110.1	-0.02%	24.3	79.1	17.5	57.1
Feedlot		# 2	84.92%	604.4	107.3	2.49%	23.4	81.6	16.9	58.9
Feedlot	open	# 1	80.56%	449.7	108.5	1.40%	2.9	224.0	2.1	161.7
Feedlot		# 2	78.49%	434.9	119.2	-8.27%	3.2	233.7	2.3	168.7
Pasture	closed	# 1	83.48%	607.2	120.1	-9.11%	19.0	81.6	13.7	58.9
Pasture		# 2	81.07%	604.3	141.1	-28.21%	20.7	81.5	14.9	58.8
Pasture	open	# 1	79.74%	458.2	116.4	-5.75%	2.5	244.9	1.8	176.7
Pasture		# 2	79.26%	466.0	121.9	-10.76%	2.1	236.7	1.5	170.9
Slurry	closed	# 1	85.44%	611.7	104.2	5.27%	12.7	64.2	9.5	48.2
Slurry		# 2	84.71%	622.3	112.3	-2.09%	11.4	64.2	8.5	48.2
Slurry	open	# 1	81.94%	530.2	116.9	-6.22%	3.8	161.0	2.9	120.9
Slurry		# 2	83.37%	538.6	107.4	2.36%	3.8	166.2	2.9	124.8
					average	-4.9%				
					Std. Dev.	9.0%				

Gas Produced During 20ºC Manure and Straw Trial

	Weight of CH4 (g)	Weight of CO2 (g)	Carbon Mass Balance Based on Theoretical Carbon						
			Begin. Carbon (g Carbon / g mol wt) *Initial VS	Final Carbon (g Carbon/ g mol wt) *Final VS	Carbon From CH4 g Carbon	Carbon From CO2 g Carbon	Total Final g Carbon from VS and Gasses	% Carbon loss (Begin C -Total Final C)/ Begin C	% Carbon Conversion (Begin C- residual C)/ Begin C
Feedlot closed # 1	12.5	112.9	430.9	362.7	18.1	21.6	402.4	6.62%	15.84%
Feedlot # 2	12.1	116.4	430.9	360.8	17.5	22.2	400.6	7.05%	16.27%
Feedlot open # 1	1.5	319.7	430.9	268.5	2.1	61.1	331.7	23.02%	37.70%
Feedlot # 2	1.7	333.5	430.9	259.6	2.4	63.7	325.8	24.40%	39.75%
Pasture closed # 1	9.8	116.4	430.9	362.5	14.2	22.3	399.0	7.42%	15.88%
Pasture # 2	10.7	116.3	430.9	360.8	15.5	22.2	398.5	7.54%	16.28%
Pasture open # 1	1.3	349.4	430.9	273.6	1.9	66.8	342.2	20.58%	36.52%
Pasture # 2	1.1	337.8	430.9	278.2	1.6	64.6	344.3	20.10%	35.45%
Slurry closed # 1	6.8	95.3	448.3	365.2	9.5	17.5	392.2	12.53%	18.55%
Slurry # 2	6.1	95.3	448.3	371.5	8.5	17.5	397.5	11.33%	17.13%
Slurry open # 1	2.1	239.0	448.3	316.5	2.9	43.9	363.3	18.96%	29.40%
Slurry # 2	2.0	246.7	448.3	321.6	2.8	45.3	369.7	17.53%	28.28%
							average	14.8%	25.6%
							Std. Dev.	6.7%	9.9%

Ratio of carbon Mass to Weight = 120/201= 0.6
From McCarty, Perry (1971) for municipal waste

20º Manure and Straw trial

Carbon Balance Based on Measured Carbon

		Total Weight (g)	% Dry Wt.	% Vol. Sol.	% Carbon	Total Begin. Carbon (g)	Ending Total Weight (g)	% dry weight	% volatile solids	Actual % Carbon (measured)
Feedlot closed	# 1	5100	16.31%	86.77%	44.17%	367.4	4946	14.51%	84.66%	43.59%
Feedlot	# 2	5100	16.31%	86.77%	44.17%	367.4	4957	14.36%	84.92%	43.44%
Feedlot open	# 1	5100	16.31%	86.77%	44.17%	367.4	2674	20.88%	80.56%	41.13%
Feedlot	# 2	5100	16.31%	86.77%	44.17%	367.4	2691	20.59%	78.49%	40.44%
Pasture closed	# 1	5100	16.31%	86.77%	44.17%	367.4	4922	14.78%	83.48%	43.35%
Pasture	# 2	5100	16.31%	86.77%	44.17%	367.4	4943	15.08%	81.07%	43.76%
Pasture open	# 1	5100	16.31%	86.77%	44.17%	367.4	2815	20.41%	79.74%	40.28%
Pasture	# 2	5100	16.31%	86.77%	44.17%	367.4	2795	21.03%	79.26%	41.35%
Slurry closed	# 1	7790	11.05%	87.22%	44.63%	384.3	7610	9.41%	85.44%	43.48%
Slurry	# 2	7790	11.05%	87.22%	44.63%	384.3	7615	9.65%	84.71%	42.67%
Slurry open	# 1	7790	11.05%	87.22%	44.63%	384.3	4548	14.23%	81.94%	42.41%
Slurry	# 2	7790	11.05%	87.22%	44.63%	384.3	4702	13.74%	83.37%	42.21%

20º Manure and Straw trial

Carbon Balance Based on Measured Carbon

Manure	Condition	Rep	Total Remaining Carbon (g)	Carbon Recovered as CO_2 or CH_4 (g)	Total Ending Carbon (g)	% Carbon Recovery	(CO_2+CH_4 Carbon) / ΔTotal Carbon	% Carbon Conversion (Beginning C- residual C)/ Beginning C
Feedlot	closed	# 1	312.8	39.73	352.5	95.9%	72.7%	14.9%
Feedlot		# 2	309.2	39.74	348.9	95.0%	68.2%	15.9%
Feedlot	open	# 1	229.6	63.25	292.8	79.7%	45.9%	37.5%
Feedlot		# 2	224.1	66.15	290.2	79.0%	46.1%	39.0%
Pasture	closed	# 1	315.2	36.49	351.7	95.7%	69.9%	14.2%
Pasture		# 2	326.2	37.68	363.9	99.0%	91.4%	11.2%
Pasture	open	# 1	231.4	68.68	300.1	81.7%	50.5%	37.0%
Pasture		# 2	243.1	66.11	309.2	84.1%	53.2%	33.8%
Slurry	closed	# 1	311.2	26.98	338.2	88.0%	36.9%	19.0%
Slurry		# 2	313.4	26.01	339.4	88.3%	36.7%	18.4%
Slurry	open	# 1	274.4	46.77	321.2	83.6%	42.6%	28.6%
Slurry		# 2	272.7	48.16	320.8	83.5%	43.2%	29.0%
					average	87.8%	54.8%	24.9%
					Std. Dev.	7.0%	17.0%	10.3%

30º Manure trial

Beginning Conditions

	Beginning Total Weight (g)	Beginning % Dry Wt.	Beginning % Vol. Sol.	Beginning Total Volatile Solids (g)	Beginning Non-Volatile Solids (g)	Ending Total Weight (g)	Ending % dry weight
Feedlot closed # 1	5000	13.90%	87.42%	607.8	87.4	4569	8.86%
Feedlot # 2	5000	13.90%	87.42%	607.8	87.4	4551	8.75%
Feedlot open # 1	5000	13.90%	87.42%	607.8	87.4	440	88.85%
Feedlot # 2	5000	13.90%	87.42%	607.8	87.4	414	88.19%
Pasture closed # 1	5000	13.90%	87.42%	607.8	87.4	4508	8.86%
Pasture # 2	5000	13.90%	87.42%	607.8	87.4	4552	8.74%
Pasture open # 1	5000	13.90%	87.42%	607.8	87.4	440	88.31%
Pasture # 2	5000	13.90%	87.42%	607.8	87.4	419	89.01%
Slurry closed # 1	7777	8.94%	87.42%	607.8	87.4	7275	5.27%
Slurry # 2	7777	8.94%	87.42%	607.8	87.4	7294	5.80%
Slurry open # 1	7777	8.94%	87.42%	607.8	87.4	417	87.66%
Slurry # 2	7777	8.94%	87.42%	607.8	87.4	431	88.04%
Slurry w/ inoc # 1 closed	9721	7.76%	86.00%	649.0	105.6	9171	4.27%
Slurry w/ inoc # 2	9721	7.76%	86.00%	649.0	105.6	9140	4.34%
Slurry w/ inoc # 1 open	9721	7.76%	86.00%	649.0	105.6	483	89.29%
Slurry w/ inoc # 2	9721	7.76%	86.00%	649.0	105.6	491	89.19%

30º Manure trial

Ending Conditions

			Ending % volatile solids	Ending Total Volatile Solids (g)	Ending Non-Volatile Solids (g)	Change in non-volatile solids (initial-final)/initial)	CH4 Prod. mls/gvs	CO2 Prod. mls/gvs	Liters of CH4	Liters of CO2
Feedlot	closed	# 1	79.07%	320.0	84.7	3.13%	196.6	230.0	119.5	139.8
Feedlot		# 2	78.87%	314.2	84.2	3.73%	209.7	239.7	127.4	145.7
Feedlot	open	# 1	77.82%	304.2	86.7	0.84%	6.2	710.9	3.8	432.1
Feedlot		# 2	76.24%	278.4	86.7	0.78%	6.1	685.3	3.7	416.5
Pasture	closed	# 1	79.48%	317.5	82.0	6.23%	193.7	234.2	117.7	142.3
Pasture		# 2	79.92%	318.0	79.9	8.61%	222.8	258.1	135.4	156.8
Pasture	open	# 1	78.15%	303.7	84.9	2.90%	5.6	661.2	3.4	401.9
Pasture		# 2	77.82%	290.2	82.7	5.38%	6.8	714.5	4.1	434.3
Slurry	closed	# 1	79.33%	304.3	79.3	9.28%	205.5	218.4	124.9	132.7
Slurry		# 2	78.99%	334.4	88.9	-1.73%	205.3	213.4	124.8	129.7
Slurry	open	# 1	76.04%	277.9	87.6	-0.18%	15.8	719.6	9.6	437.4
Slurry		# 2	76.02%	288.5	91.0	-4.06%	13.4	693.0	8.1	421.2
Slurry w/ inoc closed		# 1	76.58%	299.9	91.7	13.16%	141.6	164.7	91.9	106.9
Slurry w/ inoc		# 2	77.00%	305.8	91.3	13.53%	179.1	192.7	116.2	125.1
Slurry w/ inoc open		# 1	76.85%	331.4	99.8	5.49%	39.2	667.0	25.4	432.9
Slurry w/ inoc		# 2	76.45%	334.8	103.1	2.38%	45.9	652.8	29.8	423.6
					average	4.3%				
					Std. Dev.	5.0%				

Gas Produced During 30ºC Manure Trial

	Weight of CH4 (g)	Weight of CO2 (g)	Carbon Mass Balance Based on Theoretical Carbon Begin. Carbon (g Carbon / g mol wt) * Initial VS	Final Carbon (g Carbon/ g mol wt) *Final VS	Carbon From CH4 g Carbon	Carbon From CO2 g Carbon	Total Final g Carbon from VS and Gasses	% Carbon loss (Begin C -Total Final C)/ Begin C	% Carbon Conversion (Begin C- residual C) / Begin C
Feedlot closed # 1	85.5	276.3	362.8	191.0	147.1	62.7	400.8	-10.48%	47.35%
Feedlot # 2	91.2	287.9	362.8	187.6	156.8	65.4	409.8	-12.95%	48.30%
Feedlot open # 1	2.7	854.1	362.8	181.6	4.6	193.9	380.1	-4.77%	49.94%
Feedlot # 2	2.6	823.3	362.8	166.2	4.6	186.9	357.6	1.44%	54.20%
Pasture closed # 1	84.2	281.4	362.8	189.5	144.9	63.9	398.3	-9.78%	47.76%
Pasture # 2	96.9	310.0	362.8	189.9	166.7	70.4	426.9	-17.66%	47.67%
Pasture open # 1	2.4	794.4	362.8	181.3	4.2	180.3	365.8	-0.82%	50.03%
Pasture # 2	2.9	858.4	362.8	173.3	5.1	194.9	373.2	-2.86%	52.24%
Slurry closed # 1	89.4	262.3	362.8	181.7	153.7	59.6	395.0	-8.85%	49.92%
Slurry # 2	89.3	256.4	362.8	199.6	153.6	58.2	411.4	-13.38%	44.98%
Slurry open # 1	6.9	864.6	362.8	165.9	11.8	196.3	374.0	-3.07%	54.27%
Slurry # 2	5.8	832.6	362.8	172.2	10.0	189.0	371.2	-2.31%	52.54%
Slurry w/ inoc, # 1 closed	65.8	211.3	387.5	179.1	106.0	44.9	329.9	14.85%	53.79%
Slurry w/ inoc # 2	83.2	247.2	387.5	182.6	134.0	52.6	369.1	4.74%	52.88%
Slurry w/ inoc, # 1 open	18.2	855.8	387.5	197.9	29.3	181.9	409.1	-5.59%	48.93%
Slurry w/ inoc # 2	21.3	837.5	387.5	199.9	34.4	178.0	412.3	-6.41%	48.41%
							average	-4.9%	50.2%
							Std. Dev.	7.9%	2.8%

Ratio of carbon Mass to Weight = 120/201
From McCarty, Perry (1971) for municipal waste

30º Manure Trial

Carbon Balance Based on Measured Carbon

		Total Weight (g)	%Dry Wt.	% Vol. Sol.	% Carbon	Total Begin. Carbon (g)	Ending Total Weight (g)	% dry weight	% volatile solids	Actual % Carbon (measured)
Feedlot closed	# 1	5000	13.90%	87.42%	44.28%	307.8	4569	8.86%	79.07%	44.16%
Feedlot	# 2	5000	13.90%	87.42%	44.28%	307.8	4551	8.75%	78.87%	42.42%
Feedlot open	# 1	5000	13.90%	87.42%	44.28%	307.8	440	88.85%	77.82%	39.46%
Feedlot	# 2	5000	13.90%	87.42%	44.28%	307.8	414	88.19%	76.24%	40.69%
Pasture closed	# 1	5000	13.90%	87.42%	44.28%	307.8	4508	8.86%	79.48%	43.02%
Pasture	# 2	5000	13.90%	87.42%	44.28%	307.8	4552	8.74%	79.92%	41.32%
Pasture open	# 1	5000	13.90%	87.42%	44.28%	307.8	440	88.31%	78.15%	40.95%
Pasture	# 2	5000	13.90%	87.42%	44.28%	307.8	419	89.01%	77.82%	39.69%
Slurry closed	# 1	7777	10.27%	86.73%	45.14%	360.6	7275	5.27%	79.33%	43.28%
Slurry	# 2	7777	10.27%	86.73%	45.14%	360.6	7294	5.80%	78.99%	41.81%
Slurry open	# 1	7777	10.27%	86.73%	45.14%	360.6	417	87.66%	76.04%	41.22%
Slurry	# 2	7777	10.27%	86.73%	45.14%	360.6	431	88.04%	76.02%	39.47%
Slurry w/ inoc closed	# 1	9721	7.83%	85.50%	44.41%	338.2	9171	4.27%	76.58%	42.34%
Slurry w/ inoc	# 2	9721	7.83%	85.50%	44.41%	338.2	9140	4.34%	77.00%	42.26%
Slurry w/ inoc opwn	# 1	9721	7.83%	85.50%	44.41%	338.2	483	89.29%	76.85%	39.94%
Slurry w/ inoc	# 2	9721	7.83%	85.50%	44.41%	338.2	491	89.19%	76.45%	40.55%

30º Manure Trial

Carbon Balance Based on Measured Carbon

			Total Remaining Carbon (g)	Carbon Recovered as CO_2 or CH_4 (g)	Total Ending Carbon (g)	% Carbon Recovery	(CO_2+CH_4 Carbon) / ΔTotal Carbon	% Carbon Conversion (Beginning C- residual C)/ Beginning C
Feedlot	closed	# 1	178.7	209.83	388.5	126.2%	162.5%	42.0%
Feedlot		# 2	169.0	222.21	391.2	127.1%	160.0%	45.1%
Feedlot	open	# 1	154.3	198.51	352.8	114.6%	129.3%	49.9%
Feedlot		# 2	148.5	191.44	340.0	110.4%	120.2%	51.7%
Pasture	closed	# 1	171.8	208.76	380.6	123.6%	153.5%	44.2%
Pasture		# 2	164.4	237.04	401.5	130.4%	165.3%	46.6%
Pasture	open	# 1	159.1	184.49	343.6	111.6%	124.1%	48.3%
Pasture		# 2	148.0	199.93	348.0	113.0%	125.1%	51.9%
Slurry	closed	# 1	166.0	213.27	379.3	105.2%	109.6%	53.9%
Slurry		# 2	177.0	211.77	388.8	107.8%	115.4%	50.9%
Slurry	open	# 1	150.7	208.06	358.7	99.5%	99.1%	58.2%
Slurry		# 2	149.8	199.01	348.8	96.7%	94.4%	58.5%
Slurry w/ inoc	closed	# 1	165.8	150.87	316.7	93.6%	87.5%	51.0%
Slurry w/ inoc		# 2	167.8	186.55	354.4	104.8%	109.5%	50.4%
Slurry w/ inoc	open	# 1	172.2	211.24	383.5	113.4%	127.3%	49.1%
Slurry w/ inoc		# 2	177.6	212.40	390.0	115.3%	132.2%	47.5%
					average	112.1%	125.9%	49.9%
					Std. Dev.	10.9%	24.1%	4.5%

20º Manure trial
Beginning Conditions

		Beginning Total Weight (g)	Beginning % Dry Wt.	Beginning % Vol. Sol.	Beginning Total Volatile Solids (g)	Beginning Non-Volatile Solids (g)	Ending Total Weight (g)	Ending % dry weight
Feedlot closed	# 1	5000	13.75%	87.68%	602.8	84.7	4580	9.49%
Feedlot	# 2	5000	13.75%	87.68%	602.8	84.7	4621	9.38%
Feedlot open	# 1	5000	13.75%	87.68%	602.8	84.7	625	55.67%
Feedlot	# 2	5000	13.75%	87.68%	602.8	84.7	788	46.05%
Slurry closed	# 1	7777	8.84%	87.68%	602.8	84.7	7369	5.69%
Slurry	# 2	7777	8.84%	87.68%	602.8	84.7	7364	5.65%
Slurry open	# 1	7777	8.84%	87.68%	602.8	84.7	3676	11.05%
Slurry	# 2	7777	8.84%	87.68%	602.8	84.7	3067	14.85%
Slurry w/ inoc closed	# 1	9721	8.14%	86.42%	683.8	107.4	9272	5.49%
Slurry w/ inoc	# 2	9721	8.14%	86.42%	683.8	107.4	9279	5.32%
Slurry w/ inoc open	# 1	9721	8.14%	86.42%	683.8	107.4	4621	11.36%
Slurry w/ inoc	# 2	9721	8.14%	86.42%	683.8	107.4	4516	10.88%
Slurry w/ replenish	# 1	7777	8.84%	87.68%	602.8	84.7	6201	5.64%
Slurry w/ replenish	# 2	7777	8.84%	87.68%	602.8	84.7	6207	6.08%
Slurry&inocW/ replenish	# 1	9721	8.14%	86.42%	683.8	107.4	8552	5.71%
Slurry&inocW/ replenish	# 2	9721	8.14%	86.42%	683.8	107.4	8850	5.67%

20º Manure trial

Ending Conditions

			Ending % volatile solids	Ending Total Volatile Solids (g)	Ending Non-Volatile Solids (g)	Change in non-volatile solids (initial-final) / initial)	CH4 Prod. mls/gvs	CO2 Prod. mls/gvs	Liters of CH4	Liters of CO2
Feedlot	closed	# 1	80.47%	349.6	84.9	-0.19%	131.0	201.1	79.0	121.2
Feedlot		# 2	80.55%	349.0	84.3	0.51%	135.1	201.5	81.4	121.5
Feedlot	open	# 1	75.26%	261.9	86.1	-1.66%	0.6	471.2	0.3	284.0
Feedlot		# 2	75.90%	275.4	87.5	-3.25%	1.0	474.1	0.6	285.8
Slurry	closed	# 1	79.59%	334.0	85.6	-1.14%	157.0	194.9	94.6	117.5
Slurry		# 2	79.90%	332.6	83.7	1.16%	158.7	190.9	95.7	115.1
Slurry	open	# 1	79.57%	323.3	83.0	1.95%	161.9	342.5	97.6	206.5
Slurry		# 2	77.84%	354.6	101.0	-19.24%	134.6	346.1	81.1	208.6
Slurry w/ inoc closed		# 1	79.38%	404.4	105.0	2.21%	195.6	198.4	133.7	135.7
Slurry w/ inoc		# 2	79.19%	391.3	102.8	4.28%	188.7	194.4	129.0	132.9
Slurry w/ inoc open		# 1	80.10%	420.7	104.5	2.71%	39.5	319.8	27.0	218.7
Slurry W/ inoc		# 2	79.06%	388.6	102.9	4.20%	29.9	328.8	20.5	224.8
Slurry W/ replenish		# 1	80.80%	282.8	67.2	20.61%	65.1	325.7	39.2	196.3
Slurry W/ replenish		# 2	80.52%	303.6	73.5	13.23%	58.0	358.2	34.9	215.9
Slurry&inoc W/ replenish		# 1	79.39%	387.9	100.7	6.24%	48.8	282.5	33.4	193.1
Slurry&inoc W/ replenish		# 2	79.73%	399.9	101.7	5.37%	49.0	302.0	33.5	206.5
					average	2.3%				
					Std. Dev.	8.2%				

Gas Produced During 20ºC Manure Trial

		Weight of CH4 (g)	Weight of CO2 (g)	Carbon Mass Balance Based on Theoretical Carbon: Begin. Carbon (g Carbon / g mol wt) *Initial VS	Final Carbon (g Carbon/ g mol wt) *Final VS	Carbon From CH4 g Carbon	Carbon From CO2 g Carbon	Total Final g Carbon from VS and Gasses	% Carbon loss (Begin C -Total Final C)/ Begin C	% Carbon Conversion (Begin C- residual C)/ Begin C
Feedlot closed	# 1	56.5	239.6	359.9	208.7	98.0	54.9	361.6	-0.47%	42.00%
Feedlot	# 2	58.3	240.2	359.9	208.4	101.1	55.0	364.4	-1.26%	42.10%
Feedlot open	# 1	0.2	561.4	359.9	156.3	0.4	128.5	285.3	20.72%	56.56%
Feedlot	# 2	0.4	564.9	359.9	164.4	0.7	129.3	294.4	18.18%	54.31%
Slurry closed	# 1	67.7	232.3	359.9	199.4	117.5	53.2	370.0	-2.82%	44.59%
Slurry	# 2	68.5	227.5	359.9	198.6	118.7	52.1	369.4	-2.64%	44.83%
Slurry open	# 1	69.8	408.1	359.9	193.0	121.1	93.4	407.5	-13.23%	46.37%
Slurry	# 2	58.1	412.4	359.9	211.7	100.7	94.4	406.8	-13.03%	41.18%
Slurry w/ inoc closed	# 1	95.7	268.2	408.2	241.4	146.3	54.1	441.9	-8.24%	40.86%
Slurry w/ inoc	# 2	92.4	262.8	408.2	233.6	141.2	53.0	427.8	-4.79%	42.78%
Slurry w/ inoc open	# 1	19.4	432.3	408.2	251.1	29.6	87.2	367.9	9.87%	38.48%
Slurry w/ inoc	# 2	14.6	444.5	408.2	232.0	22.4	89.7	344.1	15.72%	43.17%
Slurry w/ replenish	# 1	28.1	388.1	359.9	168.8	48.7	88.8	306.3	14.88%	53.09%
Slurry w/ replenish	# 2	25.0	426.8	359.9	181.3	43.4	97.7	322.3	10.44%	49.63%
Slurry&inocW/ replenish	# 1	23.9	381.8	408.2	231.6	36.5	77.0	345.1	15.46%	43.27%
Slurry&inocW/ replenish	# 2	24.0	408.2	408.2	238.8	36.7	82.4	357.8	12.36%	41.52%
								average	4.4%	45.3%
								Std. Dev.	11.4%	5.3%

Ratio of carbon Mass to Weight = 120/201
From McCarty, Perry (1971) for municipal waste

20º Manure Trial

Carbon Balance Based on Measured Carbon

	Total Weight (g)	% Dry Wt.	% Vol. Sol.	% Carbon	Total Begin. Carbon (g)	Ending Total Weight (g)	% dry weight	% volatile solids	Actual % Carbon (measured)
Feedlot closed # 1	5000	13.75%	87.68%	44.38%	305.1	4580	9.49%	80.47%	44.82%
Feedlot # 2	5000	13.75%	87.68%	44.38%	305.1	4621	9.38%	80.55%	45.42%
Feedlot open # 1	5000	13.75%	87.68%	44.38%	305.1	625	55.67%	75.26%	39.64%
Feedlot # 2	5000	13.75%	87.68%	44.38%	305.1	788	46.05%	75.90%	40.35%
Slurry closed # 1	7777	8.84%	87.68%	44.38%	305.1	7369	5.69%	79.59%	42.95%
Slurry # 2	7777	8.84%	87.68%	44.38%	305.1	7364	5.65%	79.90%	43.66%
Slurry open # 1	7777	8.84%	87.68%	44.38%	305.1	3676	11.05%	79.57%	42.50%
Slurry # 2	7777	8.84%	87.68%	44.38%	305.1	3067	14.85%	77.84%	40.87%
Slurry w/ inoc closed # 1	9721	8.14%	86.42%	43.54%	344.5	9272	5.49%	79.38%	43.19%
Slurry w/ inoc # 2	9721	8.14%	86.42%	43.54%	344.5	9279	5.32%	79.19%	42.21%
Slurry w/ inoc open # 1	9721	8.14%	86.42%	43.54%	344.5	4621	11.36%	80.10%	41.25%
Slurry w/ inoc # 2	9721	8.14%	86.42%	43.54%	344.5	4516	10.88%	79.06%	42.17%
Slurry w/ replenish # 1	7777	8.84%	87.68%	44.38%	305.1	6201	5.64%	80.80%	44.05%
Slurry w/ replenish # 2	7777	8.84%	87.68%	44.38%	305.1	6207	6.08%	80.52%	42.59%
Slurry&inocW/ replenish # 1	9721	8.14%	86.42%	43.54%	344.5	8552	5.71%	79.39%	41.73%
Slurry&inocW/ replenish # 2	9721	8.14%	86.42%	43.54%	344.5	8850	5.67%	79.73%	41.78%

20º Manure Trial

Carbon Balance Based on Measured Carbon

		Total Remaining Carbon (g)	Carbon Recovered as CO_2 or CH_4 (g)	Total Ending Carbon (g)	% Carbon Recovery	(CO_2+CH_4 Carbon) / ΔTotal Carbon	% Carbon Conversion (Beginning C-residual C)/ Beginning C
Feedlot closed	# 1	194.7	152.86	347.6	113.9%	138.5%	36.2%
Feedlot	# 2	196.8	156.04	352.8	115.6%	144.1%	35.5%
Feedlot open	# 1	137.9	128.94	266.9	87.5%	77.1%	54.8%
Feedlot	# 2	146.4	130.02	276.4	90.6%	81.9%	52.0%
Slurry closed	# 1	180.2	170.62	350.8	115.0%	136.6%	40.9%
Slurry	# 2	181.7	170.82	352.6	115.6%	138.5%	40.4%
Slurry open	# 1	172.7	214.51	387.2	126.9%	162.0%	43.4%
Slurry	# 2	186.2	195.06	381.2	125.0%	164.0%	39.0%
Slurry w/ inoc closed	# 1	220.0	200.43	420.4	122.0%	161.0%	36.1%
Slurry w/ inoc	# 2	208.6	194.19	402.7	116.9%	142.9%	39.5%
Slurry w/ inoc open	# 1	216.6	116.80	333.4	96.8%	91.3%	37.1%
Slurry w/ inoc	# 2	207.3	112.06	319.3	92.7%	81.7%	39.8%
Slurry w/ replenish	# 1	154.2	137.51	291.7	95.6%	91.1%	49.5%
Slurry w/ replenish	# 2	160.6	141.06	301.7	98.9%	97.6%	47.4%
Slurry&inocW/replenish	# 1	203.9	113.55	317.4	92.1%	80.8%	40.8%
Slurry&inocW/replenish	# 2	209.6	119.03	328.6	95.4%	88.2%	39.2%
				average	106.3%	117.3%	42.0%
				Std. Dev.	13.7%	33.5%	5.9%

10º Manure trial
Beginning Conditions

		Beginning Total Weight (g)	Beginning % Dry Wt.	Beginning % Vol. Sol.	Beginning Total Volatile Solids (g)	Beginning Non-Volatile Solids (g)	Ending Total Weight (g)	Ending % dry weight
Feedlot closed	# 1	5000	13.58%	87.85%	596.5	82.5	4828	12.31%
Feedlot	# 2	5000	13.58%	87.85%	596.5	82.5	4880	12.64%
Feedlot open	# 1	5000	13.58%	87.85%	596.5	82.5	2786	20.50%
Feedlot	# 2	5000	13.58%	87.85%	596.5	82.5	2973	19.80%
Slurry closed	# 1	7777	8.73%	87.85%	596.5	82.5	7729	8.02%
Slurry	# 2	7777	8.73%	87.85%	596.5	82.5	7708	8.17%
Slurry open	# 1	7777	8.73%	87.85%	596.5	82.5	5960	10.16%
Slurry	# 2	7777	8.73%	87.85%	596.5	82.5	5975	10.26%
Slurry w/ inoc closed	# 1	9721	7.78%	81.12%	613.4	142.7	9654	7.15%
Slurry w/ inoc	# 2	9721	7.78%	81.12%	613.4	142.7	9639	7.19%
Slurry w/ inoc open	# 1	9721	7.78%	81.12%	613.4	142.7	7610	9.07%
Slurry w/ inoc	# 2	9721	7.78%	81.12%	613.4	142.7	7398	9.21%
Slurry w/ replenish	# 1	7777	8.73%	87.85%	596.5	82.5	7644	8.30%
Slurry w/ replenish	# 2	7777	8.73%	87.85%	596.5	82.5	7645	8.04%
Slurry&inocW/ replenish	# 1	9721	7.78%	81.12%	613.4	142.7	9544	7.19%
Slurry&inocW/ replenish	# 2	9721	7.78%	81.12%	613.4	142.7	9548	7.04%

10º Manure trial

Ending Conditions

		Ending % volatile solids	Ending Total Volatile Solids (g)	Ending Non-Volatile Solids (g)	Change in non-volatile solids (initial-final)/initial)	CH_4 Prod. mls/gvs	CO_2 Prod. mls/gvs	Liters of CH_4	Liters of CO_2
Feedlot closed	# 1	86.09%	511.8	82.7	-0.26%	0.0	80.6	0.0	48.1
Feedlot	# 2	86.89%	536.1	80.9	1.95%	0.0	85.7	0.0	51.1
Feedlot open	# 1	85.93%	490.8	80.4	2.56%	0.0	156.9	0.0	93.6
Feedlot	# 2	86.24%	507.6	81.0	1.80%	0.0	158.8	0.0	94.7
Slurry closed	# 1	86.93%	538.8	81.0	1.74%	0.7	65.6	0.4	39.2
Slurry	# 2	87.76%	552.8	77.1	6.51%	0.6	63.5	0.4	37.9
Slurry open	# 1	87.39%	529.3	76.4	7.38%	0.5	96.1	0.3	57.3
Slurry	# 2	87.06%	533.5	79.3	3.83%	0.6	100.7	0.3	60.1
Slurry w/ inoc closed	# 1	85.55%	590.3	99.7	30.15%	1.8	62.3	1.1	38.2
Slurry w/ inoc	# 2	85.57%	593.3	100.1	29.89%	1.5	62.3	0.9	38.2
Slurry w/ inoc open	# 1	85.36%	589.1	101.0	29.24%	1.2	97.7	0.7	60.0
Slurry w/ inoc	# 2	85.58%	582.9	98.2	31.20%	0.9	91.8	0.6	56.3
Slurry w/ replenish	# 1	87.42%	554.4	79.8	3.28%	0.0	88.0	0.0	52.5
Slurry w/ replenish	# 2	87.18%	535.6	78.8	4.46%	0.0	88.4	0.0	52.7
Slurry&inoc W/replenish	# 1	86.06%	590.6	95.7	32.97%	0.2	73.5	0.1	45.1
Slurry&inoc W/replenish	# 2	85.72%	576.0	95.9	32.80%	1.4	70.5	0.9	43.3
				average	13.7%				
				Std. Dev.	14.0%				
				Overall Average of all Trials	4.5%				
				Overall Standard Deviation of all Trials	11.4%				

Gas Produced During 10ºC Manure Trial

Carbon Mass Balance Based on Theoretical Carbon

	Weight of CH4 (g)	Weight of CO2 (g)	Begin. Carbon (g Carbon / g mol wt) *Initial VS	Final Carbon (g Carbon/ g mol wt) *Final VS	Carbon From CH4 g Carbon	Carbon From CO2 g Carbon	Total Final g Carbon from VS and Gasses	% Carbon loss (Begin C -Total Final C)/ Begin C	% Carbon Conversion (Begin C- residual C)/ Begin C
Feedlot closed # 1	0.0	95.0	356.1	305.6	0.0	22.0	327.6	8.01%	14.19%
Feedlot # 2	0.0	101.0	356.1	320.1	0.0	23.4	343.5	3.55%	10.12%
Feedlot open # 1	0.0	185.1	356.1	293.0	0.0	42.8	335.8	5.71%	17.73%
Feedlot # 2	0.0	187.2	356.1	303.0	0.0	43.3	346.3	2.75%	14.91%
Slurry closed # 1	0.3	77.4	356.1	321.7	0.5	17.9	340.1	4.51%	9.68%
Slurry # 2	0.3	74.9	356.1	330.1	0.5	17.3	347.8	2.33%	7.32%
Slurry open # 1	0.2	113.3	356.1	316.0	0.4	26.2	342.6	3.80%	11.26%
Slurry # 2	0.2	118.7	356.1	318.5	0.4	27.5	346.4	2.73%	10.56%
Slurry w/ inoc # 1 closed	0.8	75.5	366.2	352.4	1.4	17.0	370.8	-1.24%	3.77%
Slurry w/ inoc # 2	0.7	75.6	366.2	354.2	1.1	17.0	372.3	-1.67%	3.28%
Slurry w/ inoc # 1 open	0.5	118.5	366.2	351.7	0.9	26.7	379.2	-3.56%	3.97%
Slurry w/ inoc # 2	0.4	111.4	366.2	348.0	0.7	25.0	373.7	-2.05%	4.98%
Slurry w/ replenish # 1	0.0	103.8	356.1	331.0	0.0	24.0	355.0	0.31%	7.06%
Slurry w/ replenish # 2	0.0	104.2	356.1	319.8	0.0	24.1	343.9	3.44%	10.20%
Slurry&inocW/ replenish # 1	0.1	89.2	366.2	352.6	0.2	20.1	372.8	-1.79%	3.72%
Slurry&inocW/ replenish # 2	0.6	85.5	366.2	343.9	1.1	19.2	364.2	0.55%	6.10%
							average	1.7%	8.7%
							Std. Dev.	3.2%	4.4%
							Overall Average of all Trials	3.3%	32.9%

Ratio of carbon Mass to Weight = 120/201

From McCarty, Perry (1971) for municipal waste

10º Manure Trial

Carbon Balance Based on Measured Carbon

	Total Weight (g)	% Dry Wt.	% Vol. Sol.	% Carbon	Total Begin. Carbon (g)	Ending Total Weight (g)	% dry weight	% volatile solids	Actual % Carbon (measured)
Feedlot closed # 1	5000	13.58%	87.85%	48.81%	331.4	4828	12.31%	86.09%	43.68%
Feedlot # 2	5000	13.58%	87.85%	48.81%	331.4	4880	12.64%	86.89%	44.57%
Feedlot open # 1	5000	13.58%	87.85%	48.81%	331.4	2786	20.50%	85.93%	43.23%
Feedlot # 2	5000	13.58%	87.85%	48.81%	331.4	2973	19.80%	86.24%	43.79%
Slurry closed # 1	7777	8.73%	87.85%	48.81%	331.4	7729	8.02%	86.93%	43.52%
Slurry # 2	7777	8.73%	87.85%	48.81%	331.4	7708	8.17%	87.76%	45.58%
Slurry open # 1	7777	8.73%	87.85%	48.81%	331.4	5960	10.16%	87.39%	44.57%
Slurry # 2	7777	8.73%	87.85%	48.81%	331.4	5975	10.26%	87.06%	45.15%
Slurry w/ inoc # 1 closed	9721	7.78%	81.12%	46.80%	353.9	9654	7.15%	85.55%	43.90%
Slurry w/ inoc # 2	9721	7.78%	81.12%	46.80%	353.9	9639	7.19%	85.57%	44.78%
Slurry w/ inoc # 1 open	9721	7.78%	81.12%	46.80%	353.9	7610	9.07%	85.36%	44.26%
Slurry w/ inoc # 2	9721	7.78%	81.12%	46.80%	353.9	7398	9.21%	85.58%	44.09%
Slurry w/ replenish # 1	7777	8.73%	87.85%	48.81%	331.4	7644	8.30%	87.42%	44.10%
Slurry w/ replenish # 2	7777	8.73%	87.85%	48.81%	331.4	7645	8.04%	87.18%	43.54%
Slurry&inocW/ replenish # 1	9721	7.78%	81.12%	46.80%	353.9	9544	7.19%	86.06%	44.33%
Slurry&inocW/ replenish # 2	9721	7.78%	81.12%	46.80%	353.9	9548	7.04%	85.72%	43.96%

10º Manure Trial

Carbon Balance Based on Measured Carbon

		Total Remaining Carbon (g)	Carbon Recovered as CO_2 or CH_4 (g)	Total Ending Carbon (g)	% Carbon Recovery	(CO_2+CH_4 Carbon) / ΔTotal Carbon	% Carbon Conversion (Beginning C-residual C)/ Beginning C
Feedlot closed	# 1	259.7	21.99	281.7	85.0%	30.7%	21.6%
Feedlot	# 2	275.0	23.40	298.4	90.0%	41.5%	17.0%
Feedlot open	# 1	246.9	42.80	289.7	87.4%	50.7%	25.5%
Feedlot	# 2	257.7	43.30	301.0	90.8%	58.8%	22.2%
Slurry closed	# 1	269.7	18.40	288.1	86.9%	29.8%	18.6%
Slurry	# 2	287.1	17.78	304.9	92.0%	40.2%	13.4%
Slurry open	# 1	270.0	26.58	296.5	89.5%	43.3%	18.5%
Slurry	# 2	276.7	27.88	304.6	91.9%	51.0%	16.5%
Slurry w/ inoc closed	# 1	302.9	18.35	321.2	90.8%	36.0%	14.4%
Slurry w/ inoc	# 2	310.5	18.12	328.6	92.9%	41.8%	12.3%
Slurry w/ inoc open	# 1	305.4	27.56	333.0	94.1%	56.8%	13.7%
Slurry w/ inoc	# 2	300.3	25.73	326.0	92.1%	48.0%	15.1%
Slurry w/ replenish	# 1	279.7	24.01	303.7	91.6%	46.4%	15.6%
Slurry w/ replenish	# 2	267.5	24.11	291.6	88.0%	37.7%	19.3%
Slurry&inocW/replenish	# 1	304.2	20.20	324.4	91.7%	40.7%	14.0%
Slurry&inocW/replenish	# 2	295.4	20.32	315.7	89.2%	34.7%	16.5%
				average	90.3%	43.0%	17.1%
				Std. Dev.	2.4%	8.5%	3.6%
				Overall Average of all Trials	99.9%	87.3%	34.1%
				Overall Standard Deviation of all Trials	13.9%	43.6%	14.7%

Recheck on remaining frozen manure

	Total Weight (g)	Dry Wt.	Vol. Sol.	Beginning Total Volatile Solids (g)	Beginning Non-Volatile Solids (g)
Manure	5000	13.82%	88.25%	609.7	81.2